MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Thawing Frozen Water Pipes Electrically

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Specialist in Experimental Engineering

Engineering Bulletin No. 7

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

1921

VOLUME IV | OCTOBER, 1921 | NUMBER 5

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

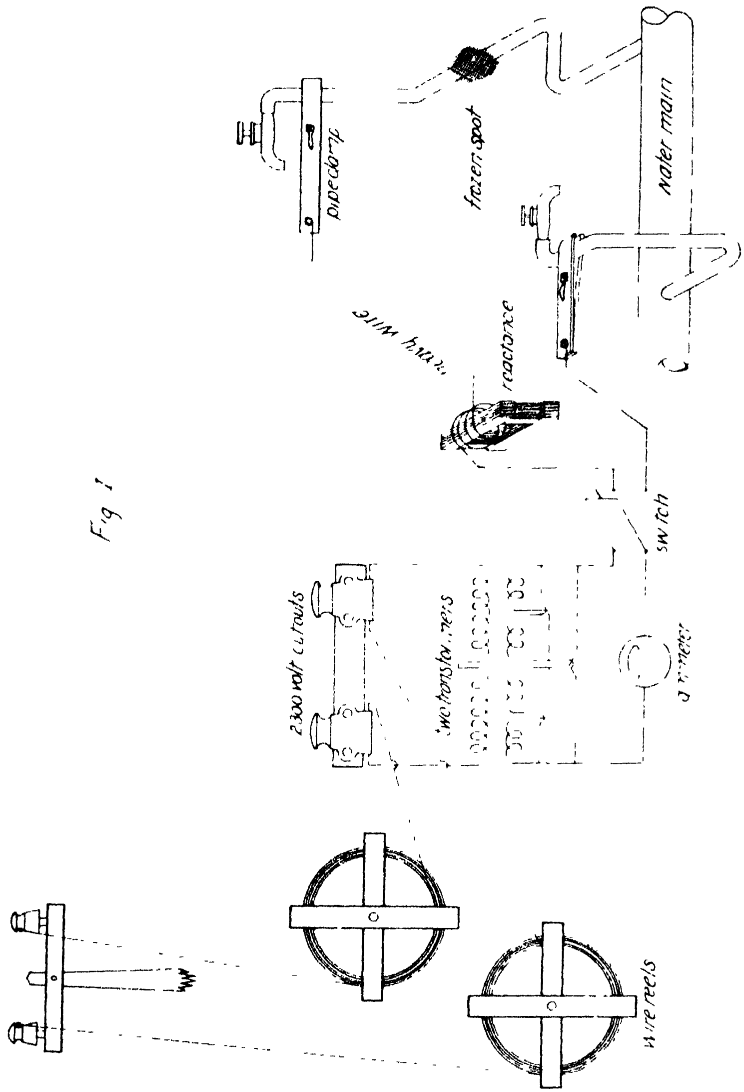
THAWING FROZEN WATER PIPES ELECTRICALLY

A locality which has enjoyed years of snowy winters occasionally finds itself in the midst of a cold snap with no snow to protect the ground from freezing. If water pipes have not been uniformly located beneath the frost line, the result will be an epidemic of frozen water pipes. Unless relieved, this soon results in actual hardships to the people in the affected houses, which can be relieved only by re-establishing water service. Frequently the pipe is frozen at the curb cock, or where the pipe crosses the parking strip to the street, or perhaps it is frozen just outside the wall where it enters the house In any event, to get at the pipe to thaw it with a torch requires more or less excavating in frozen dirt and then perhaps the pipe isn't frozen where it was thought to be This method also leads to unnecessary exposure of the pipe to further freezing. Taking into account the hard and disagreeable work and the length of time and expense incurred the digging out method is very unsatisfactory

The ideal method of thawing frozen water pipes is by electricity This has an advantage for every disadvantage of the other methods It is quick, taking but a few minutes to thaw out a hundred feet of pipe. It can be used on long stretches at a time and can be used wherever the pipe is metal. It will reach places inaccessible by other means. It does not require the disturbance of anything on the premises, nor that the exact location of the frost be found Furthermore it is comparatively cheap where there is any amount of thawing to be done.

The description and tables following are taken from an actual pipe thawing outfit used in the city of Pullman, Washington, during very cold spells when the ground has been frozen deeper than usual The outfit used, consisted of a sled on which was mounted a set of transformers such as were used for lighting service These were so connected that the line voltage was transformed from 2300 to 110 or 55 volts Power was taken from the 2300 volt city service on the

poles by means of two No. 10 wires reaching from the pole to the set of fuse cutouts at the sled, as shown in Figure 1. This wire was carried on reels on the rear of the sled Only enough wire was reeled off to reach the pole, then it was stretched up tight, and connection



made from a plug receptacle on the inside end of the coil to the cut-outs and from there to the transformers. The current used on the pipes was taken from the 110 or 55 volt secondaries and carried over large copper wire about No. 00 B & S in size. A large sized ordinary knife-switch was used to break this circuit An ammeter was also connected in this circuit for the purpose of determining the amount of current that was being used. When the length of pipe being thawed was short, the current was limited by inserting a reactance in the thawing circuit This consisted of making from six to fifteen turns of the No 00 copper wire thawing circuit on an iron core The core was made up of four square bars of laminated iron, about 6 square inches in cross section, around one leg of which the wire was coiled. The reactance was varied as required by including either part or all of the turns within the iron rectangle. For long stretches of pipe where the resistance was considerable, the transformers were connected to supply 110 volts

Following is a table which was compiled from data taken from ten different thawing jobs

Table I.

Job No	Time to thaw	Amperes	Approx Pipe Length.
1	3 Min.	320	200 feet
2	22	264	250
3	3	280	200
4	12	178	300
5	2	230	200
6	15	184	350
7	7	211	75
8	6	199	100
9	3	194	400
10	5	216	300

In all there were 138 jobs of thawing of which the following is an average resume

Table II.

Longest Job:	Shortest Job:
Thawing time, 65 min	Thawing time, 1¼ m.
Current, 184 amperes	Current, 288 amperes
Pipe size, 2 in	Pipe size, ¾ in.
Length of pipe, 275ft	Length of pipe, 150 ft
Longest Pipe:	**Shortest Pipe:**
Thawing time, 45 min	Thawing time, 11 min.
Current, 220 amperes	Current, 240 amperes
Pipe size, ¾ in	Pipe size, ¾ in.
Length of pipe, 500 ft	Length of pipe, 40 ft

Table III.

Largest current, 320 amperes	Total number of jobs, 138
Largest pipe, 2 in Water Main	Total number of days, 10½
Smallest pipe, ½ in	Least jobs in one day, 3
Longest pipe, length 500 ft	Most jobs in one day, 20
Average pipe size, ¾ in	Average jobs per day, 13 to 14
Longest time, 65 min	K W hours per job, average 1 15
Shortest time, 1¼ min	K W hours per day, about 15
Average time, 11 min	Voltage used on pipes 55 to 110

Men used:

To make 2300 volt connections on poles, 2 To handle wires to frozen pipes, 1 or 2 Foreman, 1

The reactance, which is to be used only in the low voltage circuit, may be constructed by coiling up a few turns of the No. 00 or No 000 thawing wire around a core of laminated iron Solid iron is unsatisfactory, but a bundle of small rods or wire, or strips of sheet iron, about six square inches in cross section, should be used. The iron should be arranged to form a closed path around one side of the coil, as shown in the sketch

The reactance may be replaced with a water barrel rheostat, consisting of a 50 gallon barrel about two-thirds filled with water, to which has been added a few hand-fulls of salt, soda, or sal amoniac One electrode of sheet iron about 20 in square placed in the bottom

and another electrode movably suspended in the top of the solution will supply the necessary resistance in the secondary circuit. Lowering the upper electrode will increase the current.

Following are suggestions for two types of thawing outfits. Since the transformers are used for but a few minutes at each job, it is possible to use small ones and overload them 100% to 150%

Material for Thawing Outfit No.1.

Transformer 10 to 20 K. W.--2300 to 110 volt.
2-2300 volt fuse cutouts
1-500 ampere switch.
1 large current resistance or reactance.
1-500 ampere ammeter
2 primary wires No. 10 weatherproof, about 250 ft each.
2 reels for primary wires.
2 secondary wires No. 00 or No 000. 75 and 125 ft.
2 pipe clamps.

Material for Thawing Outfit No. 2

D. C. generator, 400 to 500 ampere mavimum capacity.
1-500 ampere ammeter.
1-110 volt voltmeter
Field rheostat
2 primary wires No. 10 weatherproof about 250 ft. each.
2 reels for primary wires.
2 secondary wires No 00 or No 000. 75 and 125 ft.
2 pipe clamps.
Truck with gear attachment from engine to generator
or
Sled or wagon with gas engine connected to generator.

ENGINEERING BULLETINS

PUBLISHED BY THE

STATE COLLEGE OF WASHINGTON
ENGINEERING EXPERIMENT STATION

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

VOL. IV JANUARY, 1922 Number 8

Well and Spring Protection

By M. K. SNYDER

Municipal and Sanitary Engineer

ENGINEERING BULLETIN No. 9

Engineering Experiment Station

H. V. CARPENTER, Director

1922

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28th, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21 st, 1911. This was followed by later appropriations In April, 1919, this department was officially designated, Engineering Experiment Station

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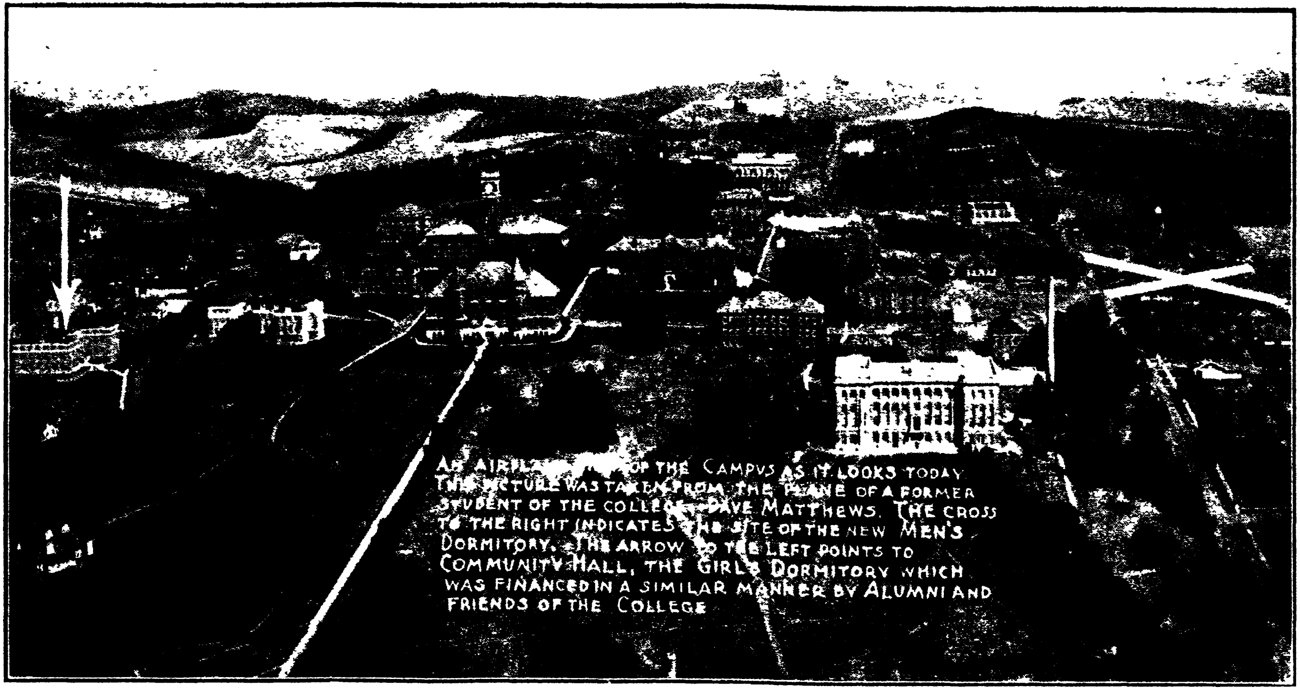


AN AIRPLA[illegible] OF THE CAMPUS AS IT LOOKS TODAY. TH[illegible] PICTURE WAS TAKEN FROM THE PLANE OF A FORMER STUDENT OF THE COLLEGE, DAVE MATTHEWS. THE CROSS TO THE RIGHT INDICATES THE SITE OF THE NEW MEN'S DORMITORY. THE ARROW TO THE LEFT POINTS TO COMMUNITY HALL, THE GIRLS DORMITORY WHICH WAS FINANCED IN A SIMILAR MANNER BY ALUMNI AND FRIENDS OF THE COLLEGE

Introduction

The water supply for practically all rural communities comes from one or more of five sources These are, (1) wells, (2) springs, (3) rivers and lakes, (4) canals, and (5) rain or snow-water In general, adequate protection of rivers, lakes and canals is practically impossible because of their great length and the many sources of pollution that may affect them. Rain and snow water come to earth already laden with impurities from the air The problem then, in connection with rivers, lakes and canals, and rain and snow-water, is not primarily a problem of protection but of purification

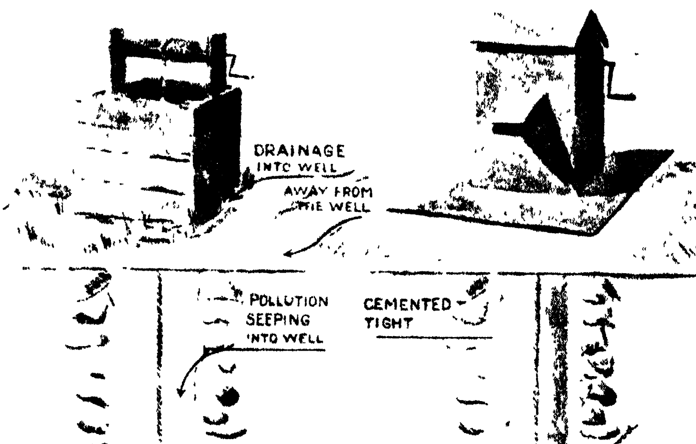


Fig. 1

In the case of wells and springs, due to the filtering and purifying action of the soil, water from such sources is usually pure unless contaminated by some man-made cause, such as privies, cesspools or barn yards See Fig 1 For wells and springs, then, the problem is primarily one of protection

Springs

The term "spring" is properly applied to water emerging from the ground at a single point or within a restricted area, but the dis-

tinction between springs and general seepage is not always very sharp. We often hear the expression "springy ground" applied to large areas where there is considerable seepage water coming to the surface. There are all gradations between the concentrated outflow characterizing the true springs and these extended damp areas known as "springy ground."

For the purpose of this bulletin, we will divide springs into three classes:

First Class. This class of springs is that in which the water, is brought to the surface at the out-crop of a porous stratum where it is underlaid by a relatively impervious one. If the surface of the impervious layer be irregular, the flow will collect in the valleys of the impervious layer and large true springs may result. If, on the other hand, the impervious layer be regular, there may be nothing but a long "seepage line," the concentration of water at any point not being more than enough to keep the surface soil damp (See Fig. 2)

Fig 2
1st Class Spring

Second Class. Under this class are considered those springs where the water-bearing stratum is confined between two more or less impervious ones These springs are artesian in character. In this class of spring, the water finds it way to the surface at points where the upper impervious layer is not present, or through breaks or cracks in this upper layer. (See Fig. 3).

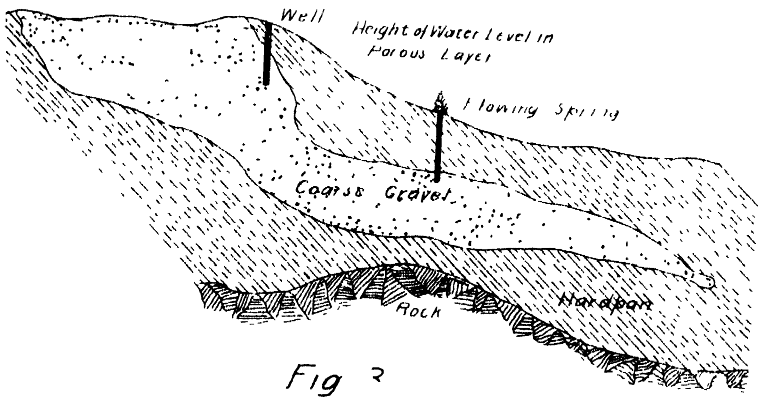


Fig 3
2nd Class Spring at Avon Mass

Third Class. This class of springs includes those in which the porous stratum in the vicinity of the spring is neither overlaid nor immediately underlaid by an impervious one They are mere overflows of the ground water and occur whenever the carrying capacity of the porous material is insufficient to convey the entire flow Naturally they are somewhat intermittent in character, often disappearing entirely in dry periods and reappearing some time after wet weather has set in The normal outflow of normal ground waters in valleys along stream lines is of this type, but true springs may develop wherever the conditions of the underlying strata are such as to cause concentration of the flow.

In sparsely settled regions, springs, if protected at their outcrop, usually furnish safe sources of supply. In thickly settled regions, where there may be many houses along the line of the underground flow, and above the outcrop of the spring, we often have springs contaminated by the drainage from privy vaults and cesspools (See Fig 4). This is particularly true in limestone regions, for in such regions the underground water flows along openings and cracks in the rock, and is not filtered through the soil at all

The chief danger comes from pollution or contamination, at and near the immediate outlet of the spring. When the water comes close to the surface, percolating water carrying pollution from the

surface may mix with it and also as it comes through the surface soil it may pick up considerable pollution, particularly if the surface about the spring outlet is exposed to the tramping of stock or disturbance by other means.

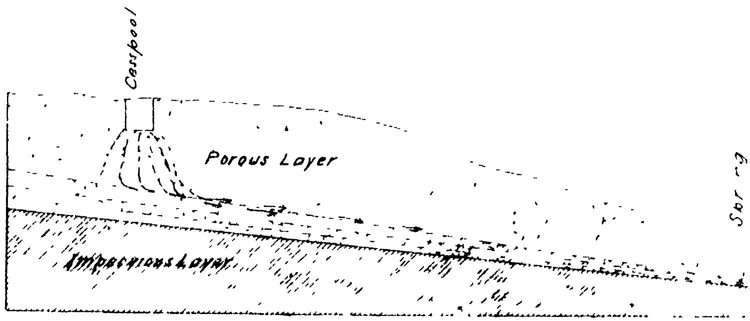


Fig 4
Cesspool Pollution of Springs

Protection of Springs. The first step, then, in insuring a wholesome supply from a spring, is to protect the outlet of the spring. The outlet of the spring should be surrounded by a fence to keep stock and other distrubing and polluting sources from approaching close to the spring. The surface of the ground around the spring should be so formed as to keep all surface drainage from passing into or over the outlet of the spring. The outlet should be further protected by being surrounded with a box, preferably of masonry, extending two or more feet into the ground and covered tightly over the top so as to exclude leaves, dust, vermin of all kinds and larger animals which might enter the spring. (See Fig. 5.)

In many cases where the spring is of the seepage type or where the emergence is not a single point, the spring may be made to yield a much larger amount of water, and at one point, by putting in open joint drain tile in a trench three or four feet deep, dug along and just above the line of outcrop of the seepage, and across the line of flow of the seepage water. In this way the discharge is brought to one point. The water may be brought to the surface through an iron or other pipe, thus preventing the possible pollution of the water at the outlet by surface drainage, or by stock.

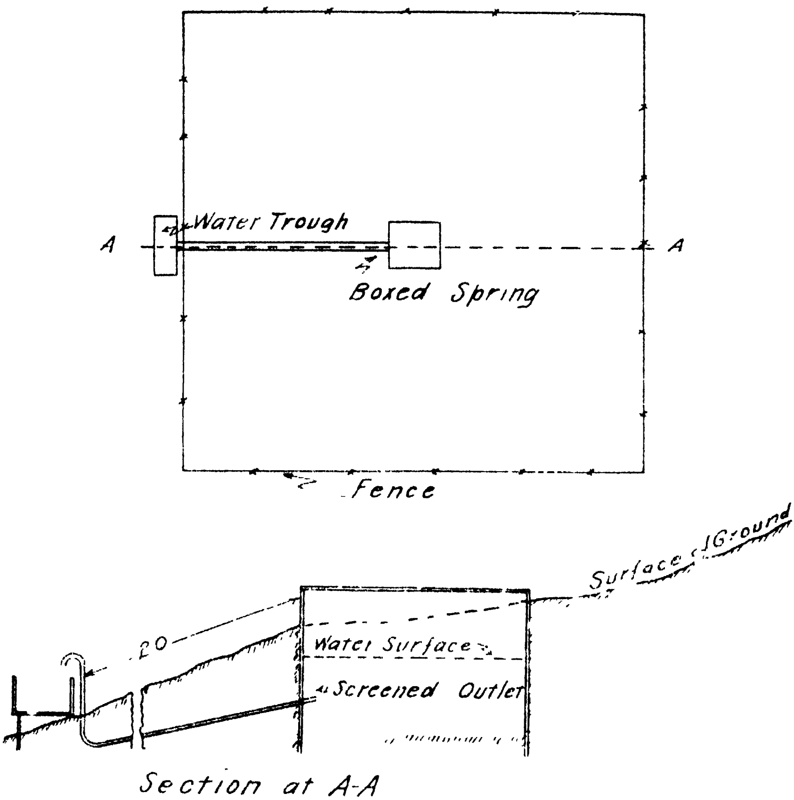


Fig. 5

Spring Properly Protected

Ground Water

Water falling upon the surface of the ground is carried away in three ways; by evaporation, by surface flow and by percolation The water which percolates into the ground and passes beyond the reach of vegetation, obeying the law of gravitation, passes on down until it reaches a layer of earth which is impervious or until it reaches a layer which is already full of water. When this layer is reached, the

water will begin to move down the slope of this layer just as surface water moves down the surface slope. The accumulation of water which thus exists in the ground is called ground water, and its surface is called the ground water level, or the water table.

The form of the water table is evidently very closely the form of the impervious layer underneath it, and as there is a rough agreement between the surface slopes and the slopes of the underlying layer of earth, the water table usually agrees roughly with the surface forms. But we must keep in mind that the lower layers of earth in many places, slope in exactly the opposite direction from the surface, and hence in these places the flow of underground water is opposite in direction from the flow of surface water. This fact is of importance in the selection of a location for a well, as the ground water should not flow from a slophole or other sources of pollution toward the well.

If the water could flow through the soil as readily as it can flow over the surface, the ground water would quickly concentrate in the valleys of the impervious layers, just as surface water concentrates in the valleys of the surface; but the flow of water through soil varies from a few feet per year, in clay and similar soils, to possibly one hundred feet per day through coarse sand or gravel These flows are so slow that the rains and other applications of water on the surface are sufficient to maintain the ground water in a vast sheet underneath the surface instead of in narrow channels. Evidently, there will be a greater concentration of water in the water table valleys than on the hills or slopes, and wells in the the valleys will yield more water than wells on the slopes and hills. On the other hand, since surface pollution is washed into the valleys, there is a much greater danger of pollution in valley wells than in wells on slopes or hills.

Since the ground water is supplied by percolation from the surface, anything which increases the surface supply of a region increases the ground water of that region. This is plainly seen in the rise of the water table with the progress of the irrigation season and its fall soon after the close of the season; also in the plentiful supply in wells in wet years and the scant supply in dry years. This same cause operates when water is supplied to the surface in a very re-

stricted area, but in this case instead of the ground water level rising over a whole region it rises only in this restricted area, causing a small mound or hill in the water table. The water flows down this hill on all sides, and thus we find the flow on one side opposite to that of the general flow. A cesspool may cause such a hill and thus pollute the water of a well actually up the main slope from it, as shown in Fig 6.

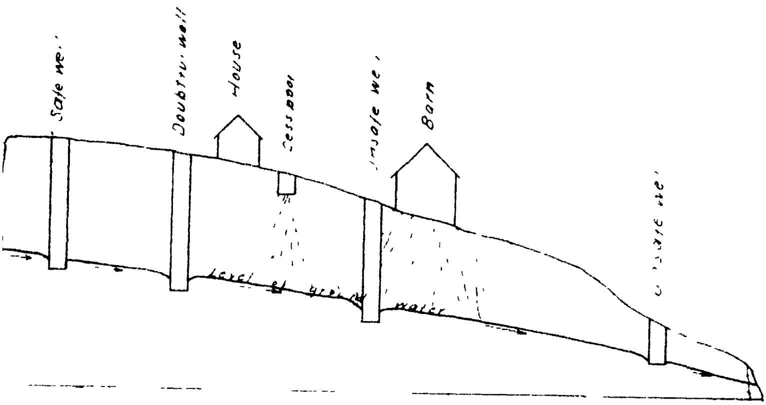


Fig 6
Cesspool and Barn Pollution of Wells

So far, we have spoken of ground water as though it were confined to a region above the first impervious layer In many places, we find several layers of earth, alternately pervious and impervious, each with an outcrop on the surface somewhere. Under such conditions, each pervious layer will contain water to a greater or lesser degree As the lower layers probably outcrop at a greater distance away, these layers will be much less liable to pollution than the surface layers, and it is for this reason that deep wells usually yield safer supplies than shallow wells (See Fig. 7)

Just as we have surface depressions that fill with water forming lakes, so we have depressions in the impervious strata underneath the surface that must fill with water up to the rim of the impervious strata If such a depression is found in successive pervious and impervious layers, as described above, the water in the intermediate

pervious layers will be under pressure and the water will rise in a well sunk into one of these layers. If the ground surface is below one of the rims of depression, a flowing well will result. Such depressions are called artesian basins

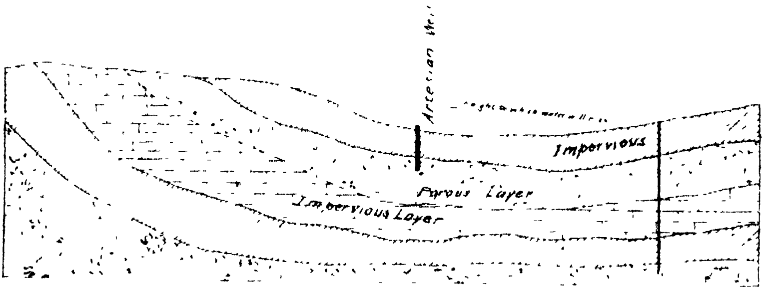
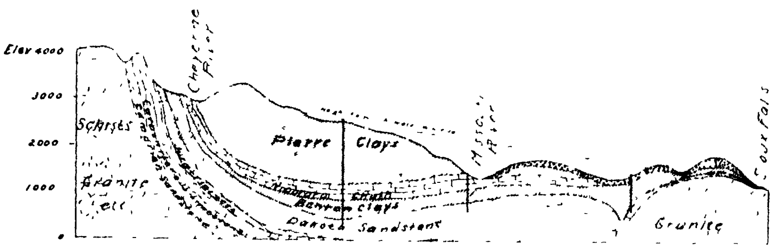


Fig 7

Figure 8 shows a section across the great Dakota Artesian Basin. The upper rim of this basin is along the foot hills of the Rocky Mountains in Montana, and the lower rim is in eastern Dakota and western Minnesota



Section through Dakota Artesian Area

Fig 8

Wherever the underlying impervious layer comes close to the surface of the ground, as is often the case in valleys or along their margins, we will find either marshes or damp, springy ground; if the layer actually outcrops, we have a seepage line or some well defined springs. Some springs are of an artesian nature, being formed by natural breaks in the upper impervious layer of an artesian area. (See Fig 3)

Wells

Wells are probably the most common source of water supply for the farm and when properly placed and cared for are certainly very convenient and furnish dependable wholesome supplies. Although no two wells are exactly alike in all particulars, there are, in reality, only a few distinct types, and for the purposes of this bulletin we will classify all wells under two heads, (1) open wells and (2) closed wells. We will define open wells as those having a surface opening of twelve inches or more in diameter, and closed wells as those wells having a surface opening of less than twelve inches in diameter. The open type well is usually a dug well from three feet to six feet in diameter. (See Fig. 9.)

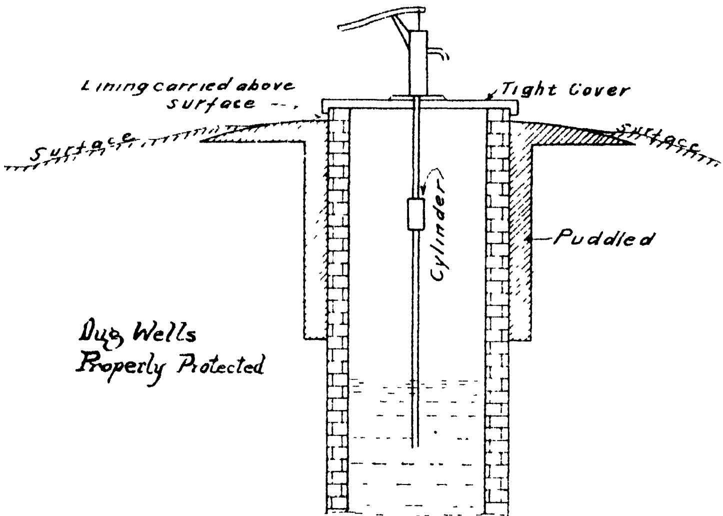


Fig. 9 (a)

The closed well is usually either driven or drilled.

Well Casings. The materials usually used for casing the open type of wells are rock, brick, tile and wood; for the closed type, wood or iron are usually used.

Wood is never a desirable material, although it may be very cheap. Near the surface of the ground it shrinks so that wide cracks are open for the entrance of vermin and polluted surface water, and

it soon rots out at the water line. The rotting of the wood favors the development of bacteria.

Rock, brick or tile when laid with uncemented points, offer easy entrance to vermin and polluted surface water. In this respect they are no better than wood, but they will not rot If laid in cement mortar, they form a tight, durable casing that will exclude all vermin and all pollution, except that entering at the bottom. For open wells of large diameter, rock or brick laid in cement mortar are recommended; for open wells of smaller diameter, glazed tile with cement points are easier to place and just as good as the stone or brick. In all cases, the earth just outside the casing should be puddled so as to close the opening between the casing and excavation. (See Fig 9)

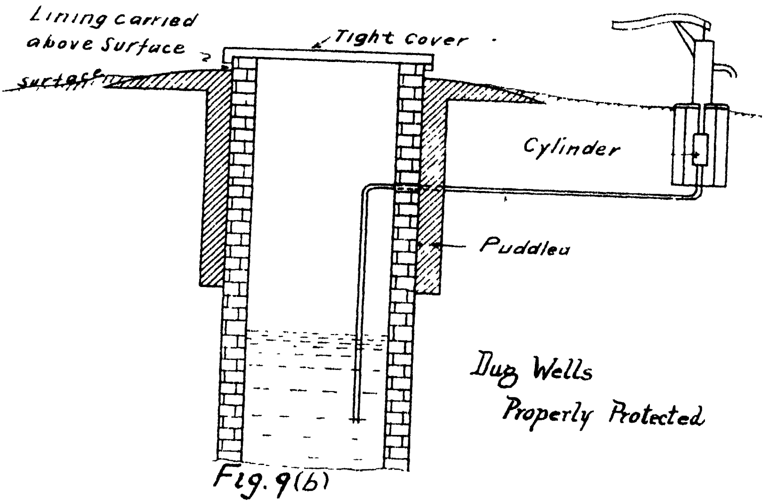
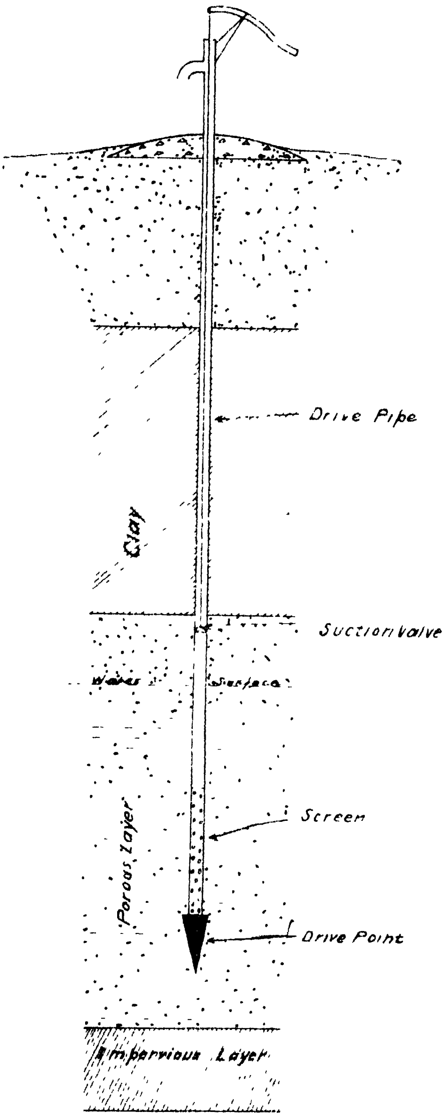


Fig. 9(b)

Iron casing with screw joints forms a water-tight casing that excludes all polluting matter except that entering at the bottom. Carefully placed iron casings of the stovepipe pattern are very good, but not so good as the screw pattern. For wells having a bore of six inches or less, iron is practically the only material used.

Protection of Wells. The safety of a well depends on the purity of the water at its source, and on the protection of the well itself from surface pollution Polluting matter enters a well in a variety



Driven Well

Fig 10

of ways; direct percolation from barnyards, cesspools, privies and slop holes; percolation from nearby pools at watering troughs, direct contamination from matter dropping from the feet of persons or animals passing over the open cover of the well; direct contamination from entrance of surface wash through holes in the casing at or near the surface of the ground, (see Fig 1.); entrance of frogs, snakes, or rodents through these same holes. All these and more must be guarded against.

Wells should be protected from contamination both above ground and below Beneath the surface of the ground, the well should be tightly cased, either with iron or with brick, stone or tile, set in Portland cement mortar to a depth of not less than ten feet. Should a water bed giving a sufficient flow of water be encountered at a greater depth than this, the well should be tightly cased down to this bed If the well is of the dug type, the opening between the brick, stone or tile casing and the sides of the excavation should be carefully filled with puddled earth as the casing is being put in, so as to shut off all chance of surface water entering the well (See Fig 9) The driven well in the process of sinking is tightly cased for its entire depth (See Fig. 10.) The drilled well should be cased tightly for some feet into the rock, the casing being made to fit the rock bore as tightly as possible

The open type of well is especially liable to contamination from the top, because of its large opening, and because of carelessness in covering this opening.

About the opening of all types of wells, the earth should be banked up high enough to make the surface slope away from the well for twenty feet or more in all directions. In this way all water falling on the ground near the well opening is quickly carried away, and all surface wash is prevented from flowing into the well or near its opening. The well opening should be tightly covered with a watertight cover, having a diameter two or three feet greater than the opening itself. This cover should rest firmly and tightly upon the casing beneath so as to prevent the entrance of rodents or vermin of any kind In fact, the cover should go down over the casing like the cover to a bucket.

It is a good plan to place the pump in a shallow well to one side of the well as shown in Fig. 9. If this is not done, care should be taken to seal or calk the pump into the cover in such a way as to prevent water passing through the pump opening

The closed type of well, on account of the small well opening is much more easily sealed than the open type, but the same precautions as to banking about the well and to covering and sealing the well opening should be taken as in the open type.

The whole aim should be to exclude all surface water from direct entrance into the well, to exclude all vermin from the well, and to exclude matter which may be brought near the well opening by stock or by persons coming to the well for water, and to keep this matter removed from the vicinity of the well opening.

Wood is probably most often used for the well cover, but it is not a suitable material By shrinking and warping, it opens the well to the direct entrance of vermin and of filth, which may be carried on to the cover by persons or stock. A reinforced concrete slab makes an ideal cover (See Figs. 9 and 10).

Safety Distance. By safety distance is meant the distance from a source of pollution at which a well may be sunk with a fair degree of safety It is evident that this distance varies with the character of the earth and with the direction of the well from the source of pollution, as referred to the ground water slope. If the well is above the source of pollution, it must be far enough away so that the formation of a hill in the water table as shown in Fig. 6 will not cause the water from this source to flow up the general slope far enough to reach the well On the other hand, if the well is below the pollution source the distance from source to well will have to be much greater, as all the polluting matter is carried down the slope, contaminating the earth for an ever increasing distance. If the earth is reasonably uniform, without any well defined channels along which the water passes, the safety distance is from 75 to 100 feet above the source of pollution to from 200 to 250 feet below the source. If there are well defined water channels in the earth, no distance below the source of pollution is safe. Should a well that is not subject to continuous pollution become contaminated by the accidental entrance of polluting matter from the surface, probably the best treatment is to

introduce into the well a small quantity of chloride of lime, and then pump the well hard so as to remove as much of the contaminated water as possible. The chloride will destroy any harmful bacteria that may be present. Care should then be taken to preclude the possibility of a second pollution. If the well is subject to continuous pollution (Fig 11) the only sure treatment is to fill it up and dig a well in a safe place or else remove the source of pollution and apply chloride, both to the source and to the well

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol 4 FEBRUARY, 1922 Number 9

Water Purification

for the

Country Home

By M. K. SNYDER

Municipal and Sanitary Engineer

ENGINEERING BULLETIN No. 10

Engineering Experiment Station

H. V. CARPENTER, Director

1922

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug 24, 1912

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Requests for copies of the engineering bulletins and inquiries for information on engineering and industrial problems should be addressed to Director, The Engineering Experiment Station, State College of Washington, Pullman, Washington.

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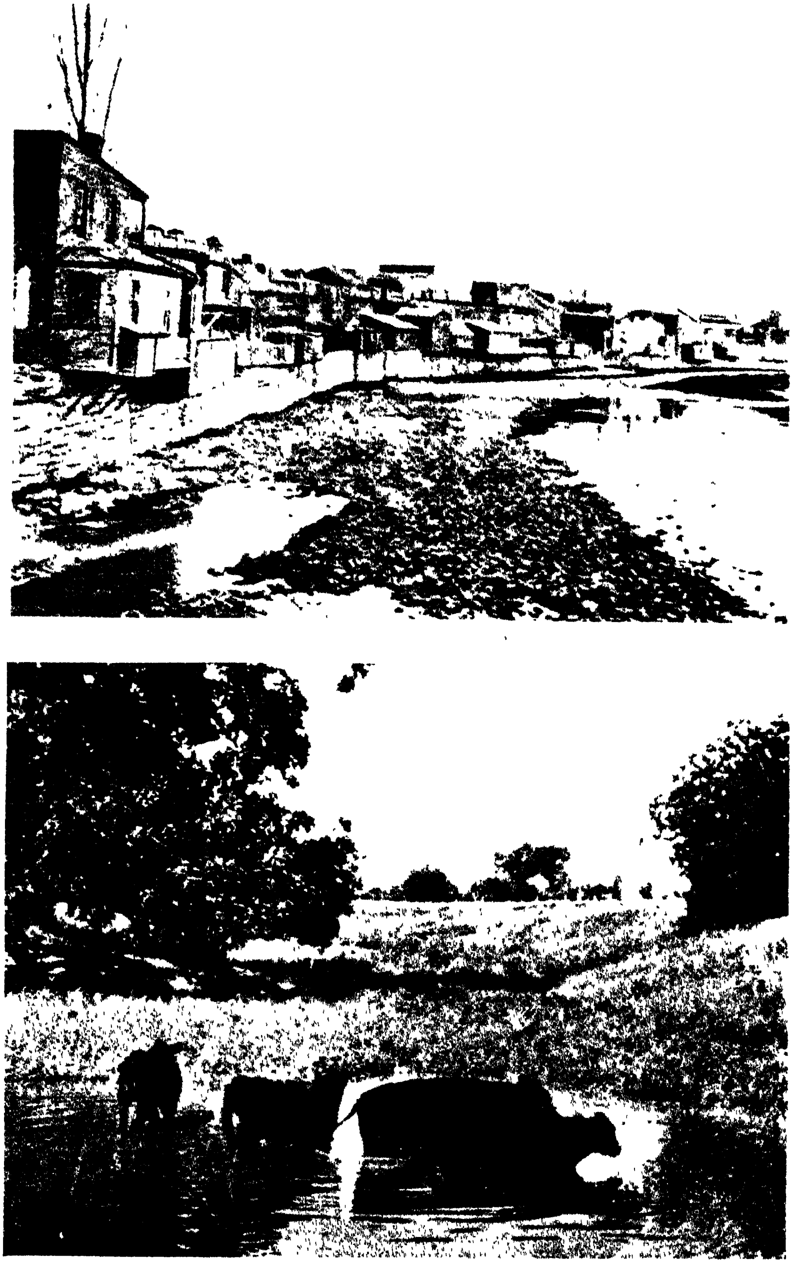


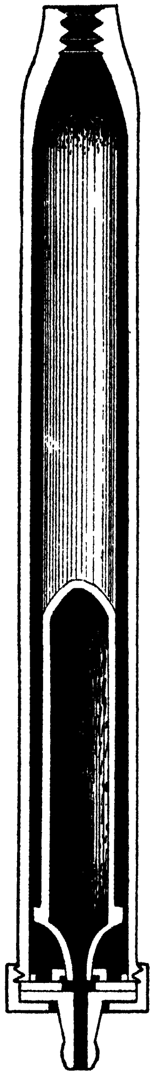
Fig. 1. Polution of Ponds and Streams

Introduction

The farmstead, being the source of supply of the food of the world, deserves to have special attention paid to its needs. Of these needs, few are greater than the need for pure water It would seem that farming regions, which are usually remote from the thickly settled districts, would find no difficulty in securing such a supply But we find that many of our intestinal diseases, such as diarrhoea, dysentery, typhoid fever, and the like, are more prevalent in the country than in the city This can mean but one thing —the farming community is very careless about its water supply

The germs of these diseases may be distributed, disseminated and carried long distances by water or by milk and vegetables which have been contaminated by water These diseases are also spread over restricted areas by flies and other insects which breed in refuse and filth It would seem, then, that the vital problems confronting the farmer are (a) the problem of securing a water supply that is sufficient in quantity and that is at all times safe and wholesome, and (b) the closely related problem of the careful and economical disposal of the wastes in which flies breed and on which they feed

The importance of pure water for drinking has been repeatedly demonstrated. Disease is frequently traced to the use of impure water from wells polluted by cess-pools, barnyard seepage, or other sources of impurities. The water may be clear, ordorless and tasteless and still contain dangerous disease germs In such case, only a chemical and a bacteriological analysis will reveal the danger, and such an analysis should always be secured if the water is at all doubtful. Such an analysis, costing but a small part of a doctor's bill, to say nothing of the discomfort to the sick one, will enable the user to tell whether purification is necessary.



Pasteur Filter

Fig. 1

In other cases, the pollution is evident from the color, taste, or odor of the water and from these alone it will be known that precautions are necessary.

Purification of Water

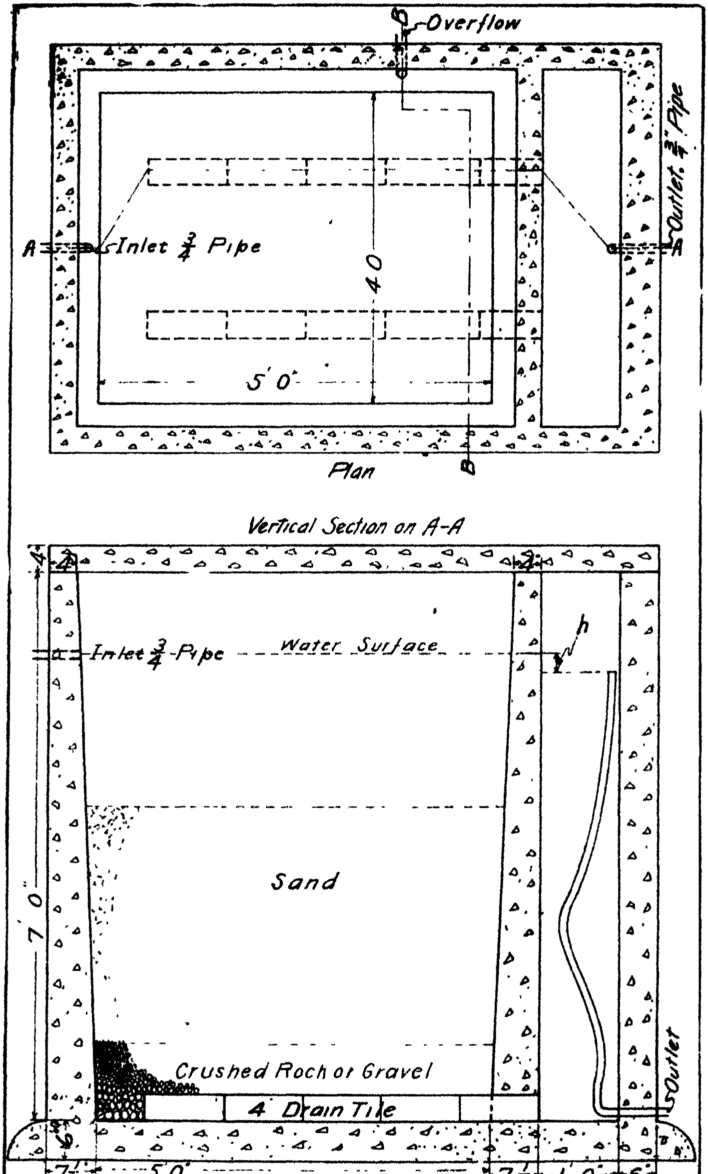
There are two general methods for the treatment of water for the removal of impurities; (a) mechanical treatment by screens and filters, and (b) chemical treatment, by the addition of chemicals.

Mechanical Treatment

Filters. Faucet screens and filters are of almost no value in the purification of water. Comparatively coarse particles of mineral matter and long slender threads of green or blue algae may be removed from the water by passing it through the set of four or five fine brass wire screens, such as can be purchased, ready for attach ment to the faucet, at the five-and ten-cent counter of any variety store or from an oily-tongued agent at twenty-five to fifty cents. So far as real purification is concerned, **these accomplish nothing.** The same results can be obtained by straining the water through two or three thickness of cheesecloth. There is only one type of faucet filter that accomplishes any real purification. This type consists of an inner tube of unglazed stoneware or porcelain and an outer metal casing, tightly attached to the outlet of the supply pipe, to protect the earthenware filter and to bring all parts of the filter into equal use.

Its operation is very slow, requiring several minutes to pass a teakettle full of water. To maintain its efficiency both as to passing and as to purifying water, it must be boiled out once or twice a week Because it operates so slowly, it is an aggravation to anyone wishing to secure water, and for this reason but few of them are found in use.

Large filters of a similar type are sometimes constructed to furnish a filtered supply for drinking purposes only. The stoneware filter is quite large, so that the amount required at one time for drinking can be had without waiting for the filter. The outside container itself may be of a semi-porous character so that the evaporation of the water from its outer surface will keep the water within the container cool enough for use; the cooling principle is the same as that involved in the use of the canvas water-bag.



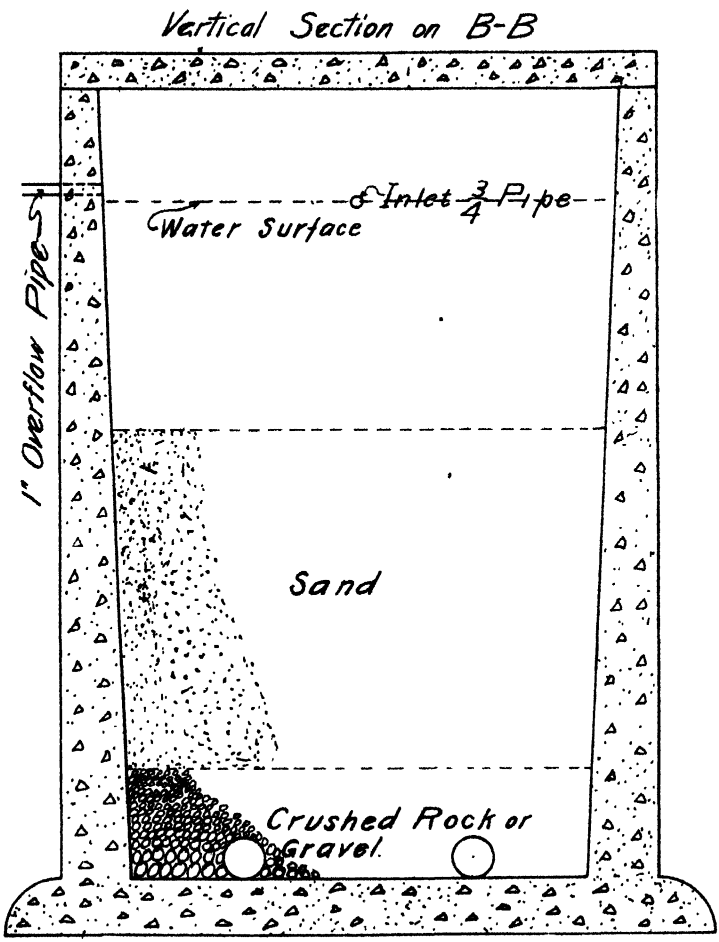
SAND FILTER. FIG. 2a.

If the supply is taken from a well and requires to be filtered as described above to insure its wholesomeness, the best treatment is that suggested in the paragraph on "Safety Distance" in Bulletin No. 9 on "Well and Spring Protection."

The Sand Filter. Where comparatively large quantities of water are to be filtered, the sand filter is the type of filter used. The general plans for the construction of such a filter are shown in Figure 2. (a and b).

The materials used in construction of the filter box or tank should be either good concrete or else good brick laid in cement mortar. The inlet and outlet and overflow pipes should be built into the walls of the filter so that there can be no leakage around them. The open spaces in the crushed rock or coarse gravel shown in the bottom of the filter furnishes a collecting basin so that the whole area of the filter is brought into operation. The sand layer, at the time of construction, should not be less than about three feet deep. Depths greater than five feet are more expensive without giving added safety. The water should be kept at a depth of two feet or more over the top of the sand, so that the surface of the sand will not be disturbed by any possible currents from the entering water or from other sources The sand required for a filter is about the same as a "good plastering sand." It should be screened through a sieve of ten or twelve meshes per linear inch (fly screen), to remove all vegetable matter, coarse particles, clay lumps, etc. The best results are obtained by using, for the filter sand, a sand that will pass through a screen having about twenty meshes to the inch and that will not pass throught a screen having 50 meshes to the inch (screens Nos. 20 and 50); but such screening materially increases the cost. The Chamber "B" (Fig. 2) is necessary to make it possible to control the rate of flow of water through the filter. The rising outlet pipe in this chamber should be a piece of flexible hose with the upper end held at the proper height by being fastened to the wall of the filter by a cord or wire.

Operation of the Filter. When the filter is completed, raise the end of the rubber hose above the level of the inlet pipe; then fill the filter with water, taking care to disturb the surface of the sand as



SAND FILTER. FIG. 2b.

little as possible. Now, lower the end of the hose about one and one-half inches below the level of the inlet; turn on the water in the inlet pipe and the filter is in operation. The water passing through the filter for the first two or three days should be allowed to waste, after which time it may be turned into the cistern or reservoir. The filter gives best results when operating continuously at a fixed rate. To make this possible, the reservoir or cistern should be provided with an overflow.

The rate of operation should be about fifty gallons per square foot per day. The head "h" (Fig. 2) required to pass this quantity of water will vary with the sand used and with the length of time the filter has been in operation. When the filter is new or has just been cleaned, "h" should not be over two inches; after a month cr more service it may be twenty inches. Th filter should then be cleaned.

Cleaning the Filter. Close the inlet pipe and draw off the water from the filter. With a square pointed shovel or similar instrument, carefully remove the upper one-half or three-fourths inch of sand. Then fill the filter with filtered water, if possible, pouring the water into the filter through the discharge chamber. When the filter is full, open the inlet pipe, set the end of the discharge pipe just below the level of the inlet, and the filter is in operation again. If the filter is filled with raw water, the flow for two or three days must be wasted, as previously described.

Size Required. If the house is not provided with pressure water, but all water has to be pumped from the cistern, as used, the domestic use will average from ten to fifteen gallons per person per day. If the house is provided with pressure water and fitted with bath, toilet and other conveniences which go with pressure water, the use will be from thirty to fifty gallons per person per day. Taking all kinds of stock into consideration, the use will be about six gallons per head per day in winter and about sixteen gallons per head per day in summer. Using the average of the above figures and assuming that water must be stored for use for one-half of the year, a family of five people having twenty head of stock will require per day as follows:

Use	Regular	Storage	Total	Size of Filter Required at 50 Gal. per sq. ft. per Day
When pumping water from cistern as used				
Family use	60 gal.	60 gal.	120 gal.	
Stock use	220	220	440	
Waste	20	20	40	
			600 gal.	3 ft. x 4 ft.
With Pressure Water:				
Family use	200	200	400	
Stock use	220	220	440	
Waste	80	80	160	
			1000 gal.	4 ft. x 5 ft.

The waste from leaks in pipes, etc. in pressure water systems is usually quite large.

Modifications can be made in the above for different quantities of stock and a different number in the family.

Construction. The filter tank may be constructed of any material that is not subject to rapid decay. Occasionally we find one built of wood painted with asphaltic paint. Often they are built of brick laid in cement mortar but the best material to use in their construction is concrete. The concrete should be a rich mixture—one part cement to two parts sand to four parts crushed rock or gravel The crushed rock or gravel should contain no stones larger than one and one-half inches in greatest dimension. Rounded stones screened from gravel will be found to work better than the sharp angular ones of crushed rock. The concrete should be well tamped as it is placed in the forms.

If possible, when constructing the filter tank of concrete, the excavation should be made just equal to the outside dimensions of the tank, the side of the excavation being used for the outside forms. The bottom of the excavation is carefully smoothed to the desired shape. The forms for the side walls and the division wall are set first and these walls are put in first. At the same time, the inlet and outlet and overflow pipes are carefully set in their proper places. Some concrete should be allowed to crowd out at the bottom of the wall forms, so that the bottom of the tank, which is next put in place, will have a good bond to the side walls.

After a few days the forms are removed and the interior of the tank plastered with a mortar consisting of one part cement to one

part sand, the walls being thoroughly wet before the mortar is put on. Whenever fresh concrete is to be joined to that which is set, the surface of the old concrete should be thoroughly cleaned and wet and covered with mortar before the fresh concrete is put in place.

A good concrete slab cover is preferable but a well made wooden cover will serve very well.

Chemical Treatment

There are a great many different chemicals used in the purification of water, but most of them require an expert operator to apply them so as to get results. Some others are so injurious to health that they may be used only in carefully determined quantities and by a skilled chemist. Leaving these two classes out of consideration, we have only one or two chemicals which are available for use on the farm.

Hypochlorite Process. For the destruction of all dangerous bacteria which may be in the water ,nothing equals in efficiency and convenience ordinary Chloride of Lime. This may be obtained from almost any grocery store in small cans costing but a few cents and the amount required is so small as to make the cost almost negligible. It should be used in the following manner:

One tablespoonful of the Chloride of Lime is dissolved in ten quarts of water. This quantity is sufficient to treat 1000 gallons of water, and the operation is carried out by simply pouring the clear solution into the water to be treated and stirring thoroughly. This solution is a powerful germicide and its action is very rapid, ten minutes or so being all the time required to carry out the purification One quart of this solution is sufficient to treat effectively a tank containing 100 gallons of water, and one pint of it stirred into a 50-gallon barrel full of water will destroy any dangerous germs and make the water safe for drinking purposes.

One is cautioned against using too much of the chemical, not because it is dangerous at all, but because an undesirable odor or taste may be imparted to the water when too large amounts are used. The strength of solution indicated above, used in the manner described, will be found perfectly satisfactory. The qualities of the

water will be in no wise impaired and no undesirable conditions will arise from its use. On the other hand, dangerous water may be made safe and much sickness prevented.

The solution loses its strength if left standing open for any time but may be kept for several days in a tightly stoppered bottle. If so kept, it becomes a very handy germicide to use during the harvesting and threshing season. The water used about the cookhouse and for drinking purposes in the field and about the threshing machine can be made safe and the amount of typhoid fever and other intestinal trouble made much less.

Lime Process. Lime is sometimes used for purification of water. About two or three pounds of quicklime is required for 1000 gallons of water. If the water is very hard, a large amount must be used The quicklime is slacked in a pail of water and is then added to the cistern or reservoir full of water and stirred in thoroughly. The action of lime is much slower than that of the Chloride of Lime, as the former requires about 24 hours to sterilize the water. The chief difficulty in the use of lime is the accumulation of sediment in the bottom of the reservoir due to the settling of the lime. The bulk of sediment is many times the bulk of the lime used and frequent cleaning is necessary. The hypochlorite treatment is recommended rather than lime treatment.

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OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

VOLUME V. JULY, 1922 NUMBER 2

Water Supply Systems for the Country Home

By M. K. SNYDER
Municipal and Sanitary Engineer
and
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Specialist in Experimental Engineering

ENGINEERING BULLETIN NO. 11

Engineering Experiment Station

H. V. CARPENTER, Director

JULY, 1922

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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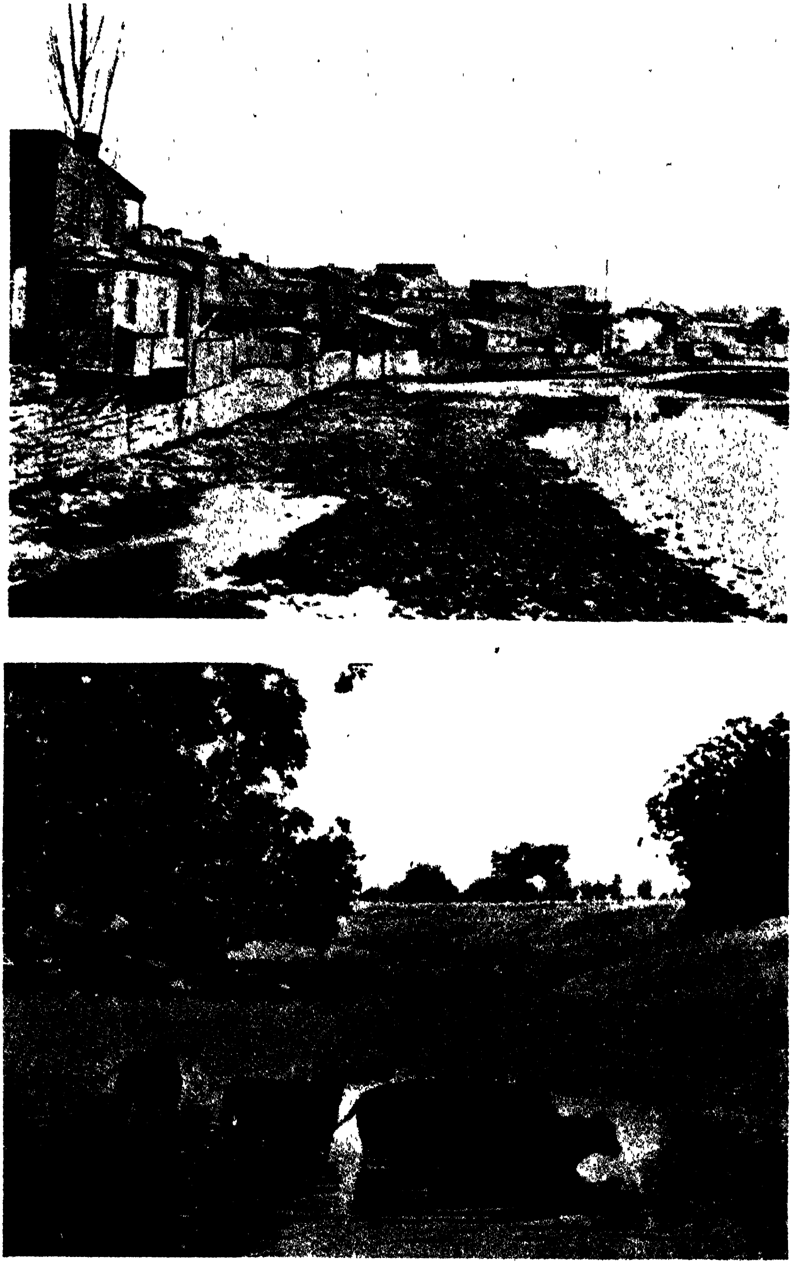


Fig. 1. Polution of Ponds and Streams

Introduction

The modern farmer is coming more and more to recognize the value of labor saving machinery in increasing the profit from his farm. Tractors, harvesters, gang plows and many other machines enable him to complete the field work in season. Large barns house his stock and tool sheds protect his machinery from weather. Everything is tending more and more toward relief from manual labor and especially from drudgery.

One of the most effective modern improvements on the farm, one that has relieved the farmer of hours of weary toil and saved the farmer's wife and daughters much of discomfort, is the modern pressure water system. No other single thing will add so much in comfort to the farm home as hot and cold water in the kitchen, and a bath and toilet in the house; and nothing is more satisfactory to the farmer when he comes in tired from a hot day in the field than to find the water troughs full of water for the stock. Such conveniences make the farm more attractive to the son who is relieved of the drudgery of pumping water for the stock after the day's work is done. They also lighten the work of the daughter in the house, making it possible to do the cooking and cleaning without carrying the water from a well some distance from the house and frequently through storms.

Such conveniences, together with the phonograph, the electric light, the telephone, the radio-phone and the automobile, help to make farm life more attractive than city life, thereby helping to relieve the problems of keeping the next generation from going to the city.

The different systems described are intended as suggestions which the farmer may adapt to meet the conditions on his farm. Exact prices and costs can best be secured from a local dealer in such supplies.

Pumps and Pumping. In general, there are only two types of pumps: (a) pumps in which the water is lifted by the action of a roughly star shaped runner, or runners, revolving rapidly within a somewhat closely fitting case, the centrifugal type. Figure 2)

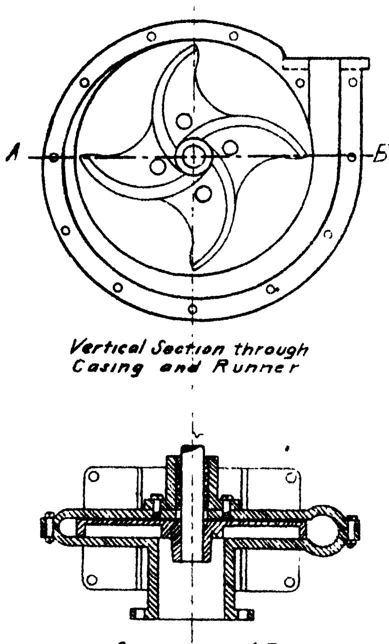


Fig. 2.

(b) pumps in which the water is lifted by the action of a sliding piston or plunger, the reciprocating type.

The ordinary centrifugal pump is not adapted for use in deep wells, but is well adapted to pump from shallow wells or from streams and canals. The lower end of the intake pipe of a centrifugal pump should be fitted with a good foot valve or else it will be necessary to prime the pump every time it is used unless the pump itself is below the water level. The efficiency of centrifugal pumps when properly installed and operated is about the same or a little less than that of reciprocating pumps.

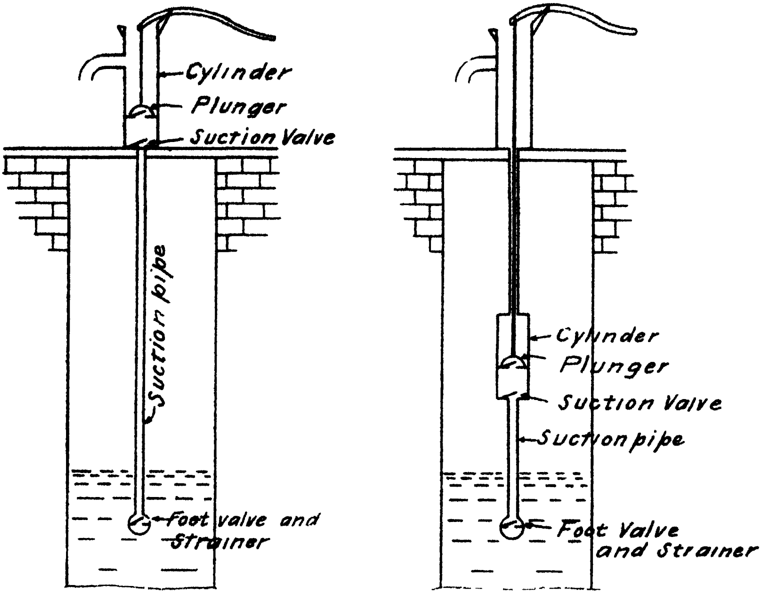


Fig. 3
Lift Pumps

Reciprocating pumps are commonly divided into two classes: the lift or suction pump (Fig. 3) and the force pump (Fig. 4). In both classes of pumps the water is drawn into the cylinder by suction, therefore the cylinder cannot be much over 25 feet above the water and work at all, and for good service it should not be over twenty feet above the water. The closer the cylinder is to the water the better.

Deep Well Pumps. As the available power is always limited pumps intended for use in deep wells or for raising water to great heights are made with cylinders of smaller diameter than those intended for use in shallow wells. In this way a greater pressure may be had from the available power and consequently the water may be lifted or forced to greater heights.

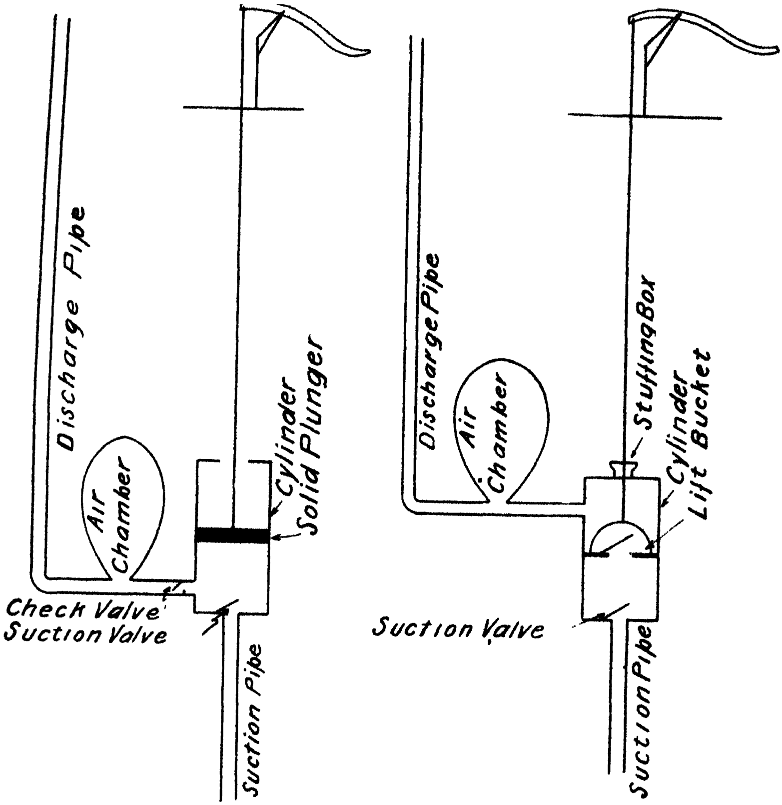
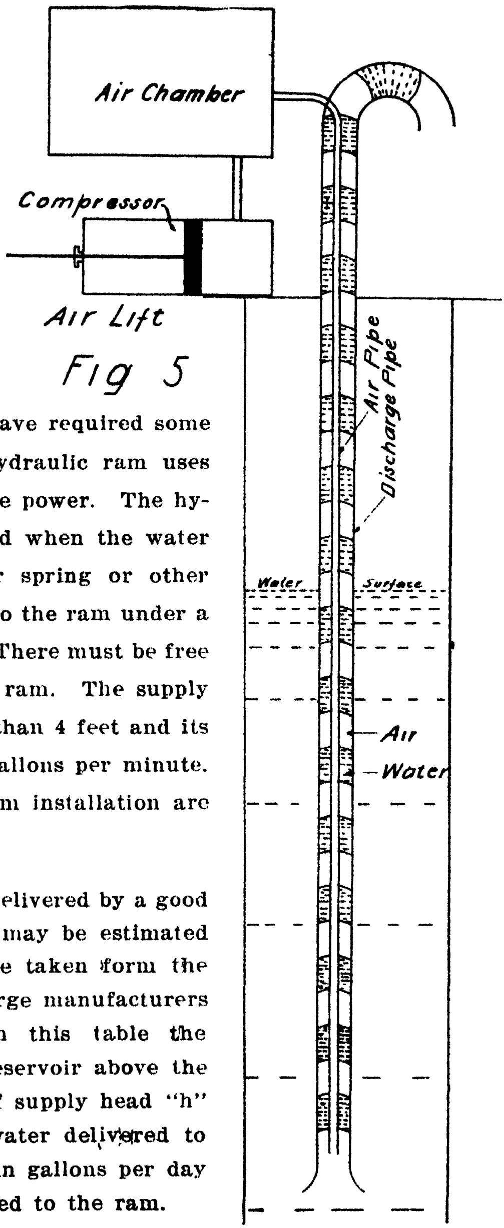


Fig. 4

Force Pumps

The Air Lift. While not a pump in the accepted use of the word, it is sometimes used for raising water from wells. This manner of raising water consists in forcing compressed air through a small pipe inserted within the casing of the well and the air emerging from the pipe near the bottom of the well can escape only by passing upward between the air pipe and the casing. As the air rises the water is carried along with it and is forced out at the top of the casing as shown in (Fig. 5). For good service the height of

lift above the surface of the water in the well should not be over one-half of the depth of the air discharge below that surface. The air lift is not recommended except for unusual conditions.

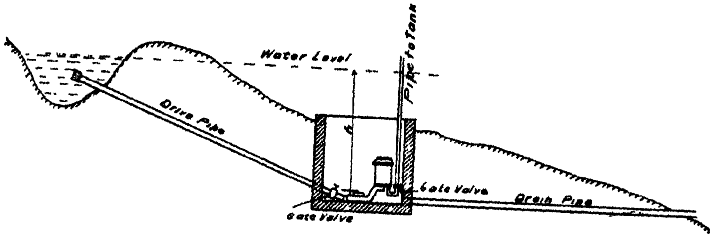


Air Lift

Fig 5

Hydraulic Ram. All the methods of raising water so far given have required some form of power. The hydraulic ram uses the water itself as motive power. The hydraulic ram may be used when the water from a flowing well or spring or other source may be supplied to the ram under a head of 4 feet or more. There must be free drainage away from the ram. The supply head should not be less than 4 feet and its supply not less than 4 gallons per minute. Two typical forms of ram installation are shown in Fig. 6.

The amount of water delivered by a good ram, properly installed, may be estimated from the following table taken form the catalog of one of the large manufacturers of hydraulic rams. In this table the height of the storage reservoir above the ram is given in terms of supply head "h" (see Fig. 6) and the water delivered to the storage reservoir is in gallons per day per gallon minute supplied to the ram.



Typical Hydraulic Ram Installations

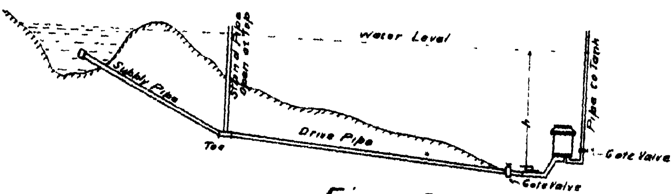


Fig 6

Height of reservoir . . 2h	3h	4h	5h	6h	7h
Gallons stored 540	336	240	192	160	137
Height of reservoir . . 8h	9h	10h	15h	20h	30h
Gallons stored 120	107	96	64	43	24

If you wish to find out whether a ram can be used in your case. and how much water you may expect to deliver into your reservoir should you install a ram, proceed as follows:

1. Determine the capacity of a washtub or other large vessel and then find out how long it takes your supply to fill it. From this you can find the supply in gallons per minute.

2. Find the difference between the level of the surface of the water in the source of supply and the place where the ram is to be installed, that is, find the supply head "h" (See Fig. 6). The ram should, if possible, be placed reasonably close to the source of supply.

3. Determine the height above the ram that the water is to be delivered to the reservoir and divide this height by the supply head "h".

4. In the table, multiply the number of gallons found underneath this quotient by the number of gallons per minute of supply, and the result will be total gallons per day delivered to the reservoir.

To illustrate. Suppose we find (1) the supply to be 7 gallons per minute; (2) the supply head "h" to be 5 feet; (3) height of a reservoir above ram 45 feet. Then 45 divided by 5 equals 9. Underneath 9h in the table we find 107, whence the number of gallons per day delivered to the reservoir is found to be 107 multiplied by 7 equals 749.

The hydraulic ram when once installed and put in operation, operates continuously, night and day, with the minimum of expense for repairs; its life is long and its first cost is not great. Wherever conditions are at all favorable for its installation it is highly recommended.

Sources of Power. The sources of power used on the farm are; windmill, gasoline engine, electric motor and water power. Any of these may be used both for pumping and for operating machines about the farm. For this reason, when selecting the source of power to be used for pumping we should consider the service which may be had from that source when the pump is not in operation.

Water Power. Wherever there is an opportunity to install a water power plant on the farm, it is found to be a most economical and dependable source of power; and when combined with an electric generator and other electric appliances, the power system is the most convenient possible. As the opportunities for farm water power installations are very few a further discussion will not be undertaken except to mention in passing that where such opportunities do exist, the farmers have frequently been very successful in supplying themselves with power by installing home made wheels. In one such instance the farmer successfully used an old cast iron pulley wheel to the rim of which he had bolted grain elevator buckets from some old threshing machinery.

In discussing the source of power, we will consider first cost, operating expense, dependability, serviceability and convenience.

A windmill ranks high in economy, the operating expense being almost negligible, but on account of varying wind velocities it is not dependable. In the hot summer days, when water is most needed, there is usually less wind than in the colder weather when water is less needed. It is not uncommon that the farmer who depends

upon the windmill for his pumping is forced to resort to hand pumping at the time of year when he can least afford the time, or else he must have a small gasoline engine for use at such times. **To avoid this difficulty, a very large storage reservoir is needed.** The reservoir must hold enough water to tide over any probable period of calm weather. A windmill used in connection with such a reservoir and with a proper distributing system may make a very convenient water supply system.

On account of the variable power output of a windmill, it is limited in service. Many attempts have been made to devise methods of storing the excess output electrically at times of high wind and making it available in times of calm, but all attempts, so far, have been only partially successful.

Gasoline Engine. The modern gasoline engine is nearly, if not quite, as dependable as the steam engine and thus takes high rank in dependability. When properly mounted on a small truck it can be moved about the farm and used for many purposes. In this way it becomes very convenient and serviceable. Its first cost is not high but it is comparatively short lived and its operating cost is fairly high. When operating at its rated capacity the gasoline engine does its work efficiently and cheaply but it will not carry overload at all. When operating at less than full load the fuel cost is very high, being nearly or quite the same as when fully loaded. The convenience of the gasoline engine may be increased by combining it with an electric generator but cost is correspondingly increased.

Electric Motor. Electric power is the most convenient and serviceable, and whenever such power can be obtained from a cross country line it is very dependable. Electric motors are not high in first cost and are comparatively long-lived, having an ordinary life of several times that of a gasoline engine. As with the gasoline engine, the high operating cost is its one drawback. The following table gives an approximate comparison between a gasoline engine and an electric motor of the same horsepower. See local dealer or catalog for exact prices.

A gasoline engine requires about .17 gallons of gasoline per brake horse-power hour. An electric motor requires about 0.9 to 1.0

H. P.	Weight in Lbs.		Floor Space Inches Approx.		Price	
	Engine	Motor	Engine	Motor	Engine	Motor
5	1200	250	30 x 50	28 x 36	$175-225	$100-150
3	650	200	25 x 45	23 x 28	80-150	75-125
2	350	150	24 x 30	21 x 24	60-125	60- 90
1	200	100	18 x 30	16 x 20	50-100	50- 65
½		60		12 x 16		35- 45

kilowatt hour per brake horse-power hour. On this basis gasoline at 30 cents per gallon is the equivalent of electricity at about 5 cents per kilowatt hour. But we should remember that an electric motor will last as long as two or more gasoline engines and for this reason we can afford to pay a little more for electricity; that the electric motor will always deliver its full rated capacity and for short times will carry a 25% overload without difficulty; that the motor operates at constant speed at all times without noise or vibration; that the gasoline engine is dependent upon a proper adjustment of the valves and sparking to give even rated capacity, and that there is always a great deal of noise and vibration.

A one-half H. P. motor is sufficiently large to run any one of the small farm machines such as fanning mill, food chopper, cream separator or churn. When it is learned that a one-half H. P. motor can be carried easily from one place to another by one man its great convenience is seen. When the farm buildings are once wired a small motor becomes of service anywhere.

Several companies are now putting out farm lighting plants consisting of a gasoline engine, an electric generator, a storage battery and switchboard. These are set up, connected and arranged with automatic controls ready for use. They are usually of small size as they are intended to produce only sufficient power for lighting the house and other farm buildings, vacuum sweepers, etc., and are not intended for heavier power purposes. The same arrangement, with larger capacity, could be used for general power plant.

Storage of Water

That the water may be convenient for use it is necessary that a pressure system be installed. Some sort of storage is necessary

unless water is obtained from a large spring or similar source located at a point above the house or from one of the new systems which automatically starts pumping as soon as the faucet is opened and stops when it is closed. There are three common ways of providing for this storage. (1) The hill reservior. (2) The elevated tank. (3) The pneumatic pressure tank. The first two of these operate alike and are here treated separately only because they are applicable to different local conditions.

The Hill Reservoir. This is valuable only for such houses as have a hill nearby that is considerably higher than the peak of the house and other farm bulidings. An excavation large enough to hold at least several days supply of water is made in the earth at the top of the hill. The excavation is lined with brick set in cement mortar, or better with a 6-inch wall of concrete and then covered over with a concrete slab or brick arch. All inlet, outlet and overflow pipes should be carefully built into the walls. The cover of the reservoir should be about two feet underground. This depth of earth cover prevents freezing in winter, and keeps the water in the reservoir from becoming warm in summer. An opening of about two feet in diameter should be brought up to the surface of the ground so that access may be had to the reservoir for purposes of examination or possible cleaning. With a force pump water is forced into this reservoir and from the reservoir is distributed to all parts of the farmstead. A pressure water heater may be installed in the house and hot and cold water may be had in the kitchen, bath room and laundry, and water may be had at the stock trough or other places at the barn, simply by opening a cock.

If the source of power operating the pump is not very dependable, the reservoir should be large enough to hold sufficient water to tide over any probable period of scant supply. Generally the reservoir should have two chambers, each connected with the inlet, outlet and overflow pipes. In this way one chamber can be used when the other is being cleaned or repaired and a supply of water is insured at all times.

The Elevated Tank. A wooden or metal tank large enough to hold the necessary supply of water may be constructed on the top

Fig. 8

of a tower sufficiently high to furnish the desired pressure. See Fig. 7. Its operation is exactly the same as that of the hill reservoir, the tower, instead of the hill, furnishing the necessary elevation. But the elevated tank is not protected from changes in temperature and the water becomes warm in summer and is liable to freeze in winter. Unless the tank and the connecting pipes are carefully surrounded with frostproofing there will be some trouble with broken pipes in cold weather. If it is desired to use the water for lawn sprinkling or fire protection purposes the tank tower should not be less than thirty feet high.

The Pneumatic Pressure Tank. Water and air are pumped into a large water and air-tight tank. The outlet pipe from this tank is at the bottom.

Since the discharge from a hill reservoir or an elevated tank is by the action of gravity only, it is necessary to increase the height of the reservoir hill or the tank to increase the pressure. On the other hand, since the pressure tank operates in opposition to gravity it is only necessary to pump more air and water into the tank to increase the pressure. In this respect the pressure tank has an advantage over the other ways of storage, since the pressure may be increased at will without additional cost. Fig. 8.

Fig. 7.

It is customary to place the pressure tank in the basement of the house or barn, or to bury it in the ground with one end projecting into the basement. It must be fitted with a water gauge so that the quantity of water in it may be determined at any time. It must also be fitted with a pressure gauge so that the pressures may not run so high as to burst the tank nor run so low that there is no discharge of water. The pressure gauge should be in a conspicuous place, such as immediately over the kitchen sink, so that the pressure will be under observation at all times.

When the tank is placed in the basement or buried in the ground, there is very little chance for the water in it to freeze in winter or get warm in summer. The principal objection to the tank is that the pressure falls off rapidly as water is drawn from the tank.

Tanks may be had of almost any capacity. The operating capacity of any tank is only three-quarters the rated capacity, as there must always be sufficient air in the tank to provide the required pressure. Any good force pump may be used to force the water into the tank, but it is best to secure a pump made for use with these tanks. These pumps are provided with an air valve through which the proper amount of air is drawn into the pump and forced into the tank with the water to keep up the pressure. Unless such provision is made, it will be necessary to force the required air into the tank with a small air pump. (The regular pump would operate as an air pump for this purpose, if the suction pipe below the cylinder could be taken from the water and everything could be kept tight).

There will be but little difference in the cost of construction of the three types. A very high tower or large tank will be costly, but so will be a large sized pressure tank or a long line of pipe to the top of a distant hill. The local condition determines the cost.

Another type of water system developed in recent years consists of a small electric motor operating a small pump. The motor operates the pump to accumulate a predetermined pressure in the system, when a pressure controlled switch opens the circuit and stops the motor. When the faucet is open the pressure is released, allowing the switch to close the motor circut thus again starting the motor. Pumping continues until the faucet has been closed and the pressure restored, when the motor is again automatically stopped. The motor gets its energy either from a commercial power line or from a farm lighting plant. Still a further development of this system consists of a small gasoline engine driven pump with automatic electric switch as above. The engine also drives a generator which charges a small storage battery for starting use alone. The starting switch closes the battery circuit through the generator which acts as a starting motor to start the gasoline engine, after which it again operates

as a charging generator. Such a machine is very compact and self contained so that it can be installed independent of any other source of power.

Hill Reservoir

Advantages

Constant temperature

Constant pressure

Low upkeep cost

Water in reservoir always available for use.

Disadvantages

Not always possible

Elevated Tank

Advantages

Constant pressure

Water in tank always available for use.

Disadvantages

Water warm in summer and freezes in winter. Consequently high upkeep cost.

Pressure Tank

Advantages

Constant temperature

Complete pressure control

Disadvantages

Variable pressures

Water in tank not all available

Medium upkeep cost.

Automatic Electric Pressure System

Advantages

Avoids cost of large pressure tank

Moderate first cost

Fresh water as used

Can be located in basement

Practically noiseless

Small upkeep costs

Automatic in action

Reliable

Requires very little attention

Disadvantages

Must have current supply from external source.

Automatic Gas Electric Pressure System

Advantages

Avoids cost of large pressure tank

Fresh water as used

Can be located in basement

Can be used remote from current supply.

Disadvantages

Reguires frequent inspection

Gasoline and oil must be kept in supply

Storage battery subject to depreciation regardless of use.

Expensive upkeep, after long continued service.

Noisy

From this summary, it is evident that the hill reservoir is to be recommended wherever there is opportunity to construct it. When the hill reservoir cannot be had, the constant temperature and moderate upkeep cost of the pressure tank probably outweigh the constant pressure of the elevated tank.

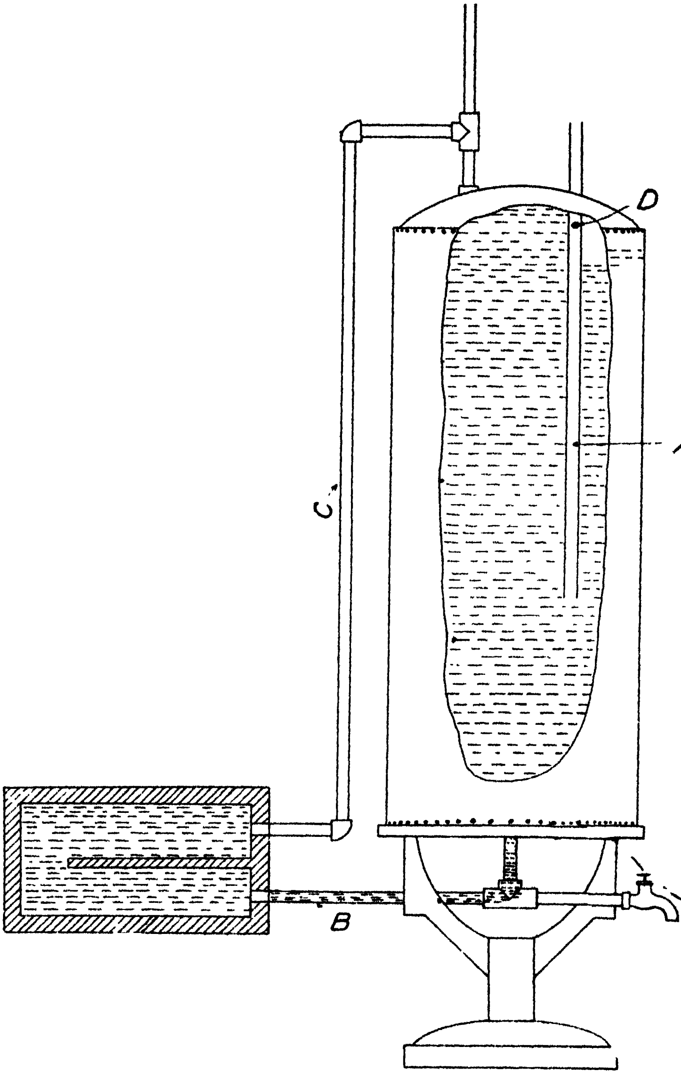
The automatic electric pressure system avoids the cost of installing a large pressure tank and recommends itself because of its constant supply of fresh water.

Household Conveniences

Probably the greatest need and the greatest possible convenience about the farm home is running water, piped to all parts of the house so that it may be had where it is needed by simply opening a faucet. A pressure water system provides for this and at the same time provides for the same conveniences about the barn and other farm buildings.

With a pressure water system, hot and cold water are both "on tap" at the kitchen sink and at the lavatory and bathtub. The inside toilet, with its privacy, protection and convenience, replaces the old outhouse with its semi-public approach, its exposure, and its inconvenience, to say nothing of its positive menace to health. In the two-story house, water may be had on the second floor as well as on the first, thus saving the labor of carrying water up and down long flights of stairs. A laundry may be provided in the basement or in some other part of the house, if desired, since it will be no longer necessary to keep near the pump to avoid the long carry of the large amount of water used on wash day. In fact, the labor involved in preparation of vegetables, in cooking, in scrubbing, in washing, and in all other work about the house where water is used, will be much reduced.

The woman in the house is as much entitled to pressure water as the man on the farm is entitled to the combined harvester or the header or other machines for reducing his labor. Besides helping the woman so much, the installation of a pressure water system helps the man about the barn. The watering trough is always full of water or quickly and easily filled without the labor of pumping. Water is handy at the hog lot and at the slop mixing barrel. In short, the help afforded by the convenience of pressure water about



Pressure Water Heater Connections

Fig. 9.

the barn is almost as great as that about the house. A pressure water system is not one-sided help, as are most farm machines, but it is a help to the whole family.

Figure 8 shows the installation of some of the household conveniences that have been mentioned. In the figure, a pressure tank is the indicated source of supply, but a hill reservoir, an elevated tank or an automatic electric, or gasoline pumping plant would serve just as well.

Figure 9 shows the best methods of making the connections to a pressure water heater tank. In the figure, pipe A is the main supply pipe, pipe B leads from the heater to the water back or heating coils in the kitchen range, pipe C leads from the heating coils to the top of the storage tank. The pipe C should always slope up from the heating coils toward the tank. D is a small hole in the main supply pipe to prevent siphonage. With the connection as shown, hot water may be had in a very few minutes after the fire in the range is started.

Fire Protection. It is not probable that any water supply system that may be installed on a farm will be adequate to put out a fire that is once under good headway; but taken at the beginning the fact that a large supply of water is available for immediate and continuous use, makes it possible to put out a fire that could not be checked by pump and bucket methods. It should be kept in mind that large pipes give much better service than small ones in putting out fires. For this reason, it is true economy to make the main pipes large enough to supply all the taps at the same time.

Costs

Pumps and Machinery. The cost of lift or force pumps of such size as are used on the farm is only a few dollars. There are so many different sizes and styles of pumps used that the actual cost prices cannot be given with any assurance of accuracy. In every case, the local dealer will be able to advise as to type and size needed and cost of same. Any local hardware dealer can furnish prices on all types of pumps, engines, rams, windmills, etc., or prices of same may be secured from popular farm supply catalogs. If there is a local company supplying electricity, always consult them as to the type of electric motor to buy; that is, direct current or one, two, or three phase alternating current.

Storage. The hill reservoir can be entirely constructed by the farmer himself, with the assistance of his regular help. In this case, the money outlay would be for material only. An excavation fourteen feet long, seven feet wide, and ten and one-half feet deep would be required for a reservoir of sufficient size to contain 4000 gallons. A reservoir of this size should be divided into two chambers, as described in the bulletin.

If a concrete lining is to be used, the excavation should be carefully trimmed to the given dimensions and the earth used for the outside forms for placing the concrete. The side walls should be six inches thick with a small amount of reinforcement to prevent cracking; the bottom, six inches thick, with sufficient reinforcement to prevent cracking caused by settlement; the top, six inches thick, reinforced to carry the two feet of earth cover safely; the partition wall twelve inches thick will require a small amount of reinforcement to prevent cracking when one chamber is empty. This construction leaves the water chambers each six feet by six feet by eight feet deep.

The materials required for the concrete lining are as follows:

Portland cement	72 sacks or 18 bbls.
Sand	5.5 cubic yards
Screened gravel or crushed rock	10.6 cubic yards

The amount of reinforcement required will depend somewhat on the character of the soil in which the excavation is made. For average conditions, the top slab will require three-eighths inch round steel rods spaced five inches apart running one way across the slab and one foot apart the other way. In good firm earth, the bottom slab should have about the same reinforcement. For the side walls, vertical rods spaced one foot apart for half the height from the bottom and two feet apart for the remainder, with a horizontal rod every two feet, should be sufficient in any soil.

The total amount of excavation required is forty cubic yards.

A wooden tank, of the same capacity as the hill reservoir noted above, placed on a steel tower thirty feet high, will cost approximately $275.00 exclusive of erection.

A 2000-gallon pressure tank will cost about $300.00 exclusive

of installation (See local dealer or consult catalogs for exact prices of above.)

The cost of the piping and installation for the three types under circumstances favorable to each, would be about the same and would depend entirely on local conditions.

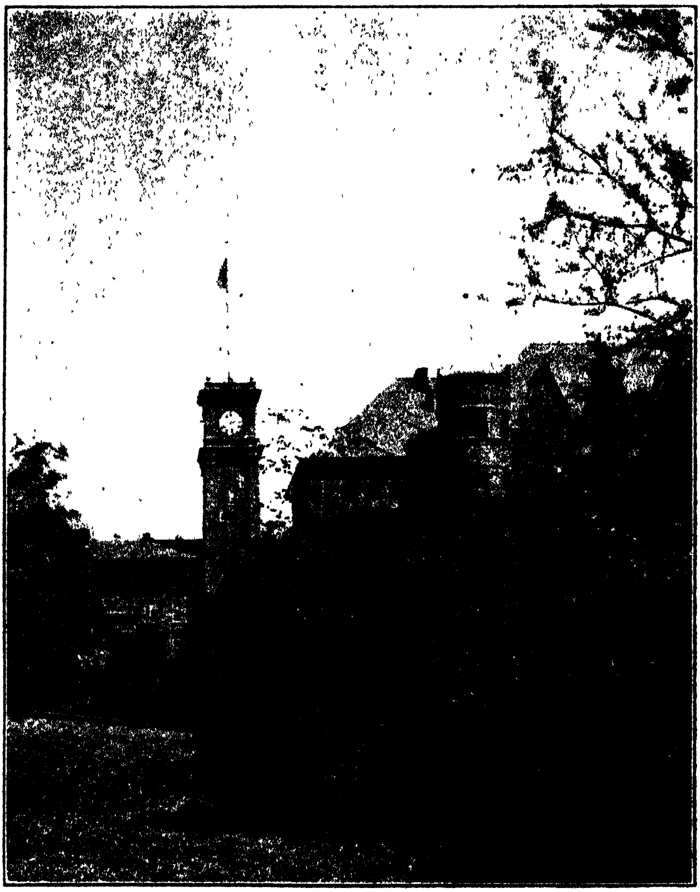
Conveniences. Since the cost of installation is usually one of the largest factors in the total cost of sanitary household equipment, it will be necessary to consult your local dealer or plumber to determine the cost of pressure water heaters, bathtubs, sinks, and other household equipment

Conclusion

If pumping is done by hand from a well of any considerable depth, the cylinder must be of small diameter and the discharge will be correspondingly small. Even when a windmill is used in direct connection with a pump, it is best to use a cylinder of small diameter so that the mill will pump with light winds (eight miles to twelve miles per hour) But when a gasoline engine or electric motor is used, power is supplied at a constant rate and the pump should be selected to use this power.

This allows the selection of a pump with larger cylinder and consequently less time is required to do the pumping. A 2 H. P. motor, connected to a pump of proper size, will deliver about 150,000 gallons of water one foot high in one hour. This is the same as pumping 1500 gallons per hour to an elevation 100 feet above the surface of the water in the well The motor will require from 5 to 6 K. W. hours of electricity to do this pumping. Or, if a gasoline engine is used, it will require from one and one-fourth, to one and one-half gallons of gasoline

Should you attempt to pump this quantity of water by hand it would require many hours of hard work. Forty-five cents worth of gasoline and the wear and tear on the engine are the dollars and cents offset against extreme weariness and a scant water supply Conveniences cannot be measured in dollars and cents. Besides the saving of time and strength, there is a satisfaction in having what you need, and this satisfaction is increased by the pleasure which replaces the drudgery



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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 5 JANUARY, 1923 Number 8

Commercial Efficiency of Single and Graded Steam Pipe Covering

By H. J. DANA

Specialist in Experimental Engineering

ENGINEERING BULLETIN No. 12

Engineering Experiment Station

H. V. CARPENTER, Director

1923

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

BOARD OF REGENTS

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INTRODUCTION

The primary object of these tests of Heat Insulating materials is to provide information leading to greater savings through the use of commercial steam pipe coverings. Routine tests were first made on samples of commercial coverings and the results were checked with those of other investigators for the purpose of establishing the accuracy of the methods used. Then the study was made of the thermal and economic efficiencies of graded combinations of commercial coverings. The arguments for graded coverings apply more particularly to two conditions. First, a great many installations at present are using one thickness of good covering and do not consider it a good investment to apply another thickness of the same priced covering, not knowing that at the comparatively low temperature at which the outside layer of covering would work, the cheaper grades of covering are almost as efficient as the most expensive grades. Second, in some new installations it should be possible to apply the graded coverings with greater economic efficiency than is possible with an application of uniform covering.

For those not already familiar with the theory of heat flow, a mathematical analysis is given for homogeneous coverings and further developed to apply to graded coverings.

Commercial Efficiency of Graded Steam Pipe Coverings.

Theoretical Analysis of Heat Flow in Pipe Coverings

The object of a mathematical treatment of heat flow in pipe coverings is to determine the amount of heat lost per sq. ft. of surface protected in terms of the physical constants of the insulating material used, so that losses may be predicted for new installations. The prime factors of importance in the relation for heat loss are temperature drop from the inside of the pipe to the surface of the covering, the conductivity of the covering, and the BTU lost per sq. ft. of surface to be protected.

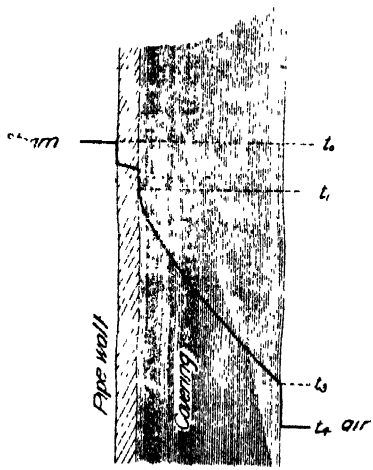

Fig 1

The total temperature drop, through both pipe and covering is distributed as shown in Figure 1, and consists of the drop from inside of the pipe, or steam temperature, to the inside surface of the insulation, from the inside surface of the insulation to the outside surface, and from the outside surface to the surrounding air.

The temperature drop through the metal walls of a covered pipe carrying saturated steam, ranges from zero at 80° pipe surface temperature to .8° at 400° pipe surface temperature and is so small it is usually ignored in calculations of heat loss.

The formula for heat loss from a flat protected surface is:

$$H_0 = \frac{A\,k\,(t_1 - t_2)\,t}{x} \qquad (1)$$

Where:

H_0 = Total loss of heat in British Thermal Units.

k = Conductivity of material in BTU per sq. ft. per degree temperature difference per hour per inch of thickness.

t_1—t_2 = Temperature drop between hotter and colder surfaces of the insulation.

A = Area of protected surface in sq. ft.

x = Thickness of insulation in inches.

t = Time in hours.

Uniform Type Covering

The formula for pipe covering is developed by considering a hollow cylinder with internal and external diameters corresponding to the covering in question, and of such length that the inner surface is one square foot in area. As the heat flows from the hot inner surface to the cooler outer surface, it encounters a constantly

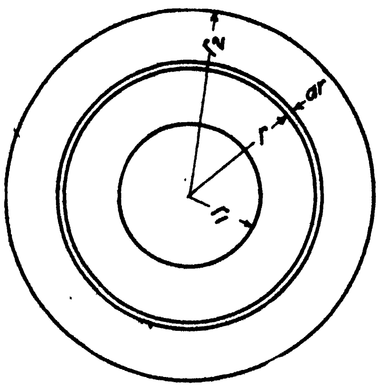

Fig. 2

increasing area and for that reason the flat surface formula cannot be directly applied. However, as in Figure 2, if a ring of infinitesimal thickness dr is considered, the flat surface formula will apply since the outer and inner surfaces of the ring approach an equal value,

Then:

$$H = A\,k\,\frac{dt}{dr} \text{ per hour} \qquad (2)$$

Where:

dt = temperature drop through the ring.

dr = infinitesimal thickness of ring.

r_1 = inside radius of covering.

r_2 = outside radius of covering.

r = radius of ring.

Then, since the length of covering was assumed such that the surface of the cylinder of radius equal to r_1, is one sq. ft., the area of the surface of the ring of radius r is:

$$A = \frac{r}{r_1}$$

Substituting in (2)

$$H = k\,\frac{r}{r_1}\,\frac{dt}{dr}$$

or,

$$dt = \frac{r_1 H}{k}\,\frac{dr}{r}$$

which is a general equation for any infinitesimal ring in the covering, and can be integrated between the limits of the pipe covering, r_1 and r_2,

$$\int_{t_1}^{t_2} dt = \frac{r_1 H}{k}\int_{r_1}^{r_2}\frac{dr}{r}$$

or,

$$t_1 - t_2 = \frac{r_1 H}{k}\,(\log_e r_2 - \log_e r_1)$$

$$H = k\,\frac{(t_1 - t_2)}{r_1 \log_e \frac{r_2}{r_1}} \qquad (3)$$

The coefficient of conductivity k is the only part of the equation which must be determined by experiment, but after once being determined for a covering for a given temperature range, the value may be used thereafter in calculating heat loss for that covering over the temperature range given. In other words, if the value of k has been determined for 85% magnesia covering over a range of temperature differences from 300 to 500 degrees Fahrenheit, it may be used in any calculation for heat loss through 85% magnesia within similar temperature limits. The value of k is not constant as has been assumed above for different temperatures, but increases as the temperature in the insulation increases and varies with different thicknesses of insulation. Therefore the value of k to be used is best derived from a plotted curve for the temperature range desired and for the approximate thickness to be used. Figure 9 shows values of k for different coverings as determined in these tests.

Graded Type Covering

The foregoing analysis deals only with coverings made up of one material throughout. If two different kinds of covering are employed on a pipe at the same time the calculation for heat loss involves the consideration of different values of k for each covering in addition to the other factors.

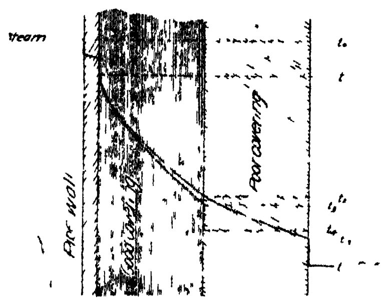

Fig 3

Since the heat loss through any one layer of a covering must be the same as the heat loss through any other layer on the same pipe at the same time, then:

$$H = \frac{k_1 (t_1 - t_2)}{r_1 (\log_e r_2 - \log_e r_1)} = \frac{k_2 (t_2 - t_3)}{r_1 (\log_e r_3 - \log_e r_2)}$$

where k_1 and k_2 are the coefficients of conductivity for the first and second coverings respectively and temperatures are as shown in Figure 3. Therefore in order to calculate the heat loss through a graded covering, it is necessary to know the value of k_1 and k_2, and these, like k, for the single covering can be determined only from actual test, at working temperatures close to those expected.

Description of Testing Machine

One of the primary requirements for testing pipe coverings is a constant and easily adjustable source of heat. This could best be realized only by the use of a special machine designed and constructed for the purpose. Such a machine was built and used very satisfactorily throughout these tests. It consists as shown in Figure 4, of a standard five inch steel pipe about 15½ feet long, filled with oil. One end was closed with a steel plate welded to the pipe. The other end was fitted with a flange to which was bolted a plate carrying a stuffing gland on the outside. Carried on bearings inside the pipe was a 2″ pipe on which was wound an insulated electric heating element. This element consisted of No. 16 iron stove pipe wire wound non-inductively around the 2″ pipe, asbestos paper being used for insulation. Leads to three separate sections of the heater were brought from the slip rings shown, into the machine through the hollow shaft extending from the 2″ heater pipe out through the stuffing gland mentioned above. A steel ribbon 3/32″ x 3/8″ wound into a spiral of 18″ pitch was attached to the heater pipe so that it stood 1/4″ above the heater element and cleared the inside of the 5″ pipe by about 1/2″. This spiral acted as a screw to both rotate the oil and give it an endwise motion through the machine. The return path was provided through the 2″ heater pipe so that when the machine was in operation the rotating heater also thoroughly stirred the oil to maintain the temperature uniform throughout.

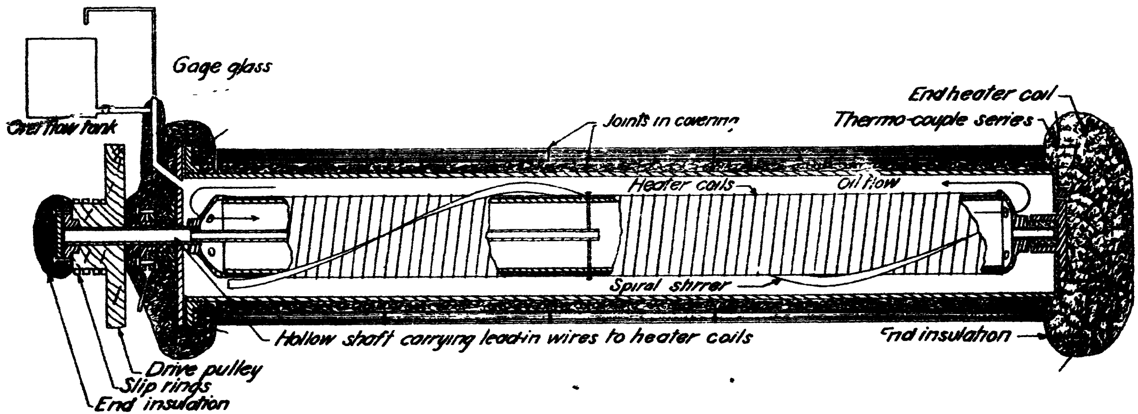

Fig. 4: Sectional view of machine for testing efficiency of pipe coverings

The heater-stirrer was rotated at 25 r. p. m. by means of a motor belted through a reduction gear to a pulley on the end of the hollow heater shaft. Slip rings adjacent to the pulley and connected to lead wires coming out between gaskets in the flanged union on the end of the hollow shaft, served to convey current to the heating element within. The current from the transformer was controlled by means of a lamp bank in series with the heater.

Oil was used as a heat conveying medium and since oil expands with a rise in temperature, provision was necessary for considerable increase in volume. An outlet was located in the end of the machine so that it would first lead off all the air and gas in the system and then as the temperature increased conduct the excess volume of oil into a reserve tank. This overflow was a glass tube 1/8″ internal diameter. By adjusting the oil level properly, the entire machine became a huge thermometer with a bulb of about 12½ gallons capacity and a 1/8″ glass stem in which 1° F equaled about 18″ length of stem.

Control of the electrical input to the heater coils made it pos sible to maintain a steady temperature in the system as indicated by the constant position of the oil level in the glass stem.

Heat was supplied to the machine through the three electric heating elements mentioned above. The electrical input was measured in watts by means of an indicating wattmeter and this was converted into heat equivalent by the constant, 3.415, which is BTU per watt hour. The heat put into the machine to hold the temperature constant represents the amount of heat that is being radiated out through the covering and if this input is divided by the surface area of the pipe, the average radiation per sq. ft. is the result. However, due to the shape and irregularities of the ends of the pipe, it is almost impossible either to measure the area accurately or put on a covering which will give the same radiation per sq. ft. as the straight part of the pipe. Since it was so uncertain and difficult to determine the end losses accurately, it was decided to eliminate them entirely from the calculations.

Control of End Losses

If two portions of a body are of the same temperature, no transfer of heat will take place. This fact was utilized in the insulation of the end portions of the machine. A coating of plastic magnesia cement was applied to the ends of the machine so that the intervening length of 5″ pipe would accommodate 14½ feet of standard sectional covering. About a dozen ¼″ holes were drilled perpendicularly into each end coating of cement and in these were inserted alternate junctions of a number of thermo couples connected in series. The remaining and opposite junctions were left against the outside surface of the cement. Over this was applied another coating of magnesia cement about 1″ thick and to the surface of this was applied a pancake heating element, which in turn was covered with a final coat of plastic cement. When the current to this auxiliary heater was properly adjusted, the temperature at the heater element is the same as the temperature at the surface of the end of the pipe and there would then be no transfer of heat, or end radiation from the machine itself. In other words, the end heater was supplying the end losses. The proper current adjustment for this auxiliary heater was determined by means of the thermo couple series connected to a galvanometer so that if all the thermal junctions of the series averaged the same temperature, no current would flow through the galvanometer and the deflection would be zero. A deflection of the galvanometer merely indicated that the end heaters were either hot or cold as compared to the end of the pipe and the current in them should be re-adjusted accordingly. Each end heater was independent of the other and so also were the thermo-couple series in each end. This arrangement made it possible to adjust temperatures so that the electrical input into the main heater represented the amount of heat radiated out through the 14½ feet of covering. Figure 5 shows the electrical circuits of the testing machine.

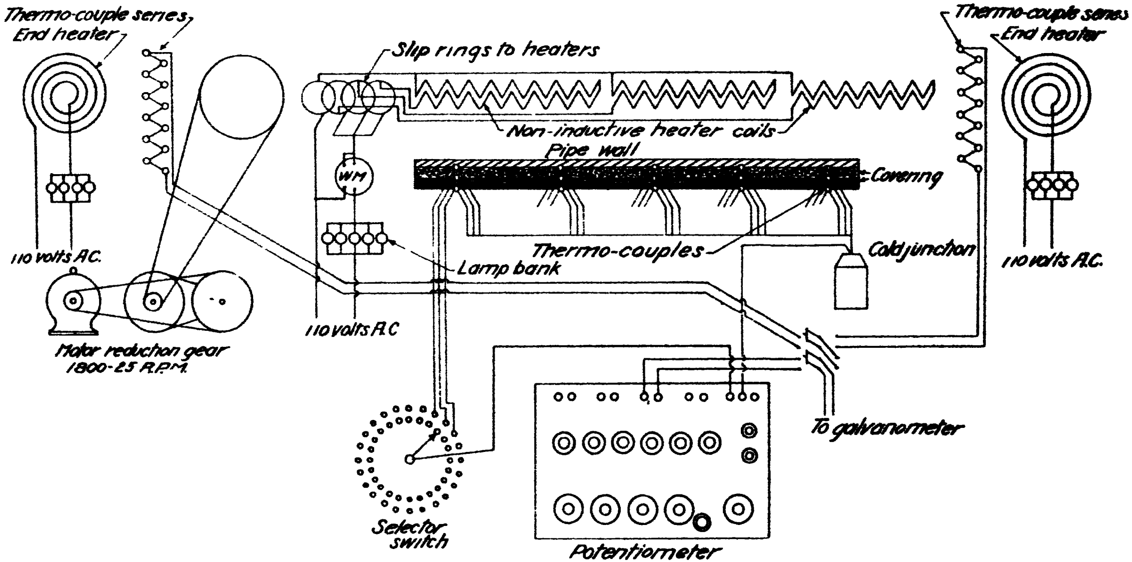

Fig 5. Diagram of circuits of machine for testing efficiency of pipe coverings

Test Measurements

Electrical input was measured with a Weston indicating wattmeter, Model 310, which was calibrated and checked frequently throughout the tests. In addition to the electrical heat energy put into the machine, account must be taken of the mechanical heat energy introduced by the mechanical stirrer into the oil. This was determined by measuring the electrical input into the stirrer motor both with and without the oil in the machine. After allowing for added losses in the motor itself due to added load, the difference was taken as the amount of mechanical energy introduced into the oil as heat. This amount was found to be 8 watts and was always considered as part of the input into the machine. Temperatures were measured by means of the average of five sets of copper-constantan thermo-couples, located as shown in Figure 5. The surface temperature of the pipe was measured rather than the temperature of the medium and for this, five couples were embedded in the metal surface of the pipe. This was done by raising a lip of steel with a cold chisel, inserting the couple junction and peening the lip of steel down over it. A similar set of five couples was inserted just under the canvas jacket of the covering to measure outside surface temperatures. Also a pilot thermometer was located in an oil filled thermometer well, drilled in the top of the flange end of the machine, for the purpose of quickly ascertaining the approximate temperature of the pipe in adjusting for taking a set of data. All the thermo-couples were tested for identity and for residual emf. A certificate from the Bureau of Standards was secured for one of the stock thermo-couples, and the rest were checked against this one. An ice bath was employed for the cold junction and emf's were measured on a new Leeds and Northrup White potentiometer with sensitive galvanometer. The standard cell for the potentiometer was frequently checked against another standard kept for the purpose. The potentiometer was also used to determine if the temperature of the machine was stable. This was done by measuring the emf. of one of the pipe couples and leaving the potentiometer connected and noting if a drift of the galvanometer reading took place during the next five minutes. If not, then the temperature was not changing and a set of data could be taken.

It required from two to four hours to establish the stability of temperatures in the covering after they had been changed. Thick coverings required a greater length of time for temperatures to become stable than did thin coverings.

Covering was applied to projecting oil pipes, shaft, etc., in order to minimize all stray heat losses from the machine.

Tests Made

Tests were made on coverings bought in the open market and applied to the pipe according to common practice in engineering work. Magnesia, air cell, "asbestocel", "carocel", "nonpareil", "sponge felt", and "multiply" were among the coverings investigated. Each new set of covering after being applied to the testing machine, was brought up to the highest testing temperature and dried several days before any data were taken, then losses were measured at successively decreasing temperatures. Previous to and during a test the room temperature was maintained constant, and as free from air currents as possible.

Sample Calculations

Data from test on standard thickness 85% magnesia:

Pipe temperature	306° Fahr.
Surface temperature of covering	114° Fahr.
Air temperature	80° Fahr.
Electrical input	610 watts.
Mechanical input	8 watts.
Total input,	618 watts.

Input per sq. ft. pipe surface

$618 \div 21.05 = 29.35$ watts per sq. ft.

B. T. U. input, $29.35 \times 3.415 = 100.35$ per sq. ft. per hr.

Outside diameter of pipe 5.6″, $r = 2.8''$

Inside diam. of coverings 5.6″, $r_1 = 2.8''$, $\log_e 2.8 = 1.0296$

Outside diam. of covering 7.6″, $r_2 = 3.8''$, $\log_e 3.8 = 1.3350$

Solving for conductivity k,

$$k = \frac{H\, r_1 (\log_e r_2 - \log_e r_1)}{t_1 - t_2}$$

$$= \frac{100.35 \times 2.8\ (1.3350 - 1.0296)}{306 - 114}$$

$= .446$ BTU/sq. ft./hr./deg. temp. diff./in. thick.

This is the value of k for single thickness magnesia at the temperature difference given. The value of k increases as the temperature difference increases—

Illustration of calculation of heat loss from a 4″ pipe:

Steam pressure	100 lbs. per sq. in.
Temp. drop in wall of pipe	.5° Fahr.
Pipe temp., steam at 100 lbs.	336.° Fahr.
Air temperature	80.° Fahr.

Outside diam. of pipe 4.5″, $r = 2.25″$

Inside diam. covering 4.5″, $r_1 = 2.25$ $\log_e 2.25 = .8109$

Outside diam. covering 6.5″, $r_2 = 3.25$ $\log_e 3.25 = 1.1787$

k at 256 degrees temp. diff. = .455 (From curve Fig. 9)

Assume surface temp. at 110 deg. Fahr.

$$H = \frac{.455\ (336 - 110)}{2.25\ (1.1787 - .8109)} = 124$$

H_s = BTU per sq. ft. of surface of covering.

$= 124 \times 2.25/3.25$

$= 86$

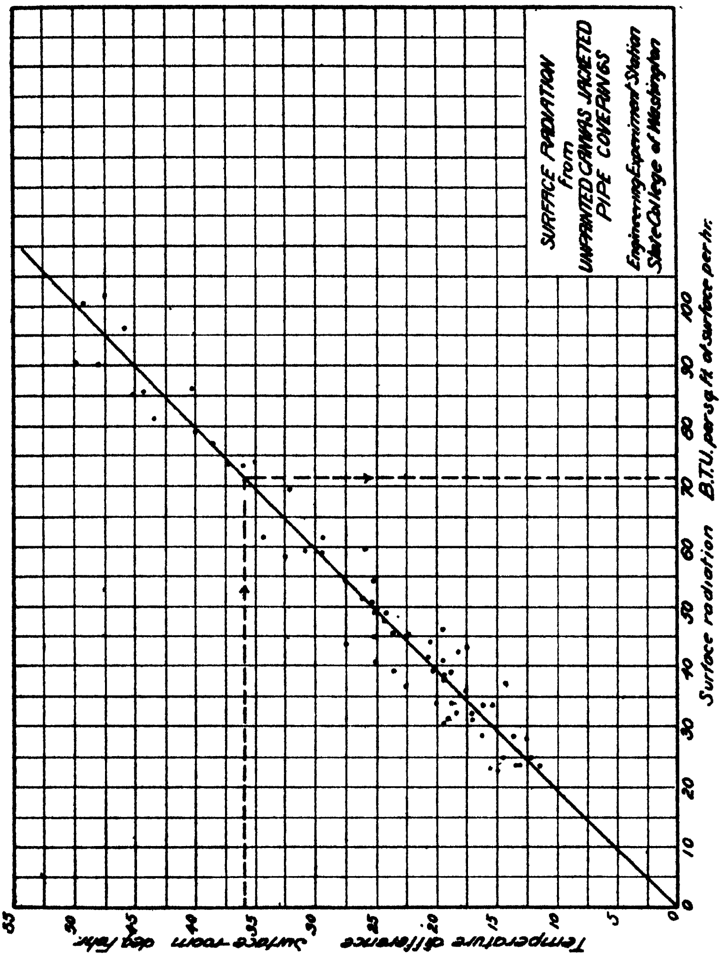

Fig. 6. Heat loss from a canvas surfaced pipe covering

From curve sheet Figure 6, a radiation of 86 BTU per square foot of covering surface will take place at a temperature difference between surface and air of 43 deg. This would make the surface temperature of the covering being investigated = 80 + 43 = 123 degrees instead of 100°. Therefore, the surface temperature in the first trial solution was assumed too low.

Repeating above solution with assumption of surface temperature of 121 deg.

$$H = \frac{.455\ (336 - 121)}{2.25 \times .3678} = 118$$

$$H_s = 118 \times 2.25/3.25 = 81.8$$

From curve sheet Figure 6 a radiation of 81.8 BTU per sq. ft. of covering surface will take place at a temperature difference of 41½ deg. which would make the surface temperature 121½ deg. which is ½ deg. from the assumed temperature and may be accepted as correct.

Graded Covering Calculations

Given, pipe size, 8″

Steam pressure, 120 lbs. per sq. in.

Steam temperature, 353½ deg. Fahr.

Temperature drop in metal of pipe, .5 deg. Fahr.

Air temperature, 80 deg. Fahr.

Covering,— 1″ magnesia and 1″ air cell

Find radiation per sq. ft. of pipe surface.

$k_1 = .46$ (magnesia)

$k_2 = .66$ (air cell).

$t_1 = 353$ deg. F.

$t_3 = 100$ deg. (assumed).

$r_1 = 4.3125,\ \log_e 4.3125 = 1.4615$

$r_2 = 6.3125,\ \log_e 6.3125 = 1.8425$

$r_3 = 8.3125,\ \log_e 8.3125 = 2.1179$

$$H = \frac{k_1(t_1 - t_2)}{r_1(\log_e r_2/r_1)} = \frac{k_2(t_2 - t_3)}{r_1(\log_e r_3/r_2)}$$

$$H = \frac{.46(353 - t_2)}{4.3125 \times .3810} = \frac{.66(t_2 - 100)}{4.3125 \times .2754}$$

$$= .28(353 - t_2) = .556(t_2 - 100) \qquad (1)$$

$t_2 = 183.7°$.

Substituting to derive H, (1)

$$H = .28(353 - 183.7)$$

$$= 51.4 \text{ BTU per sq. ft. of pipe per hour.}$$

$$H_s = 51.4 \times \frac{4.3125}{8.3125}$$

$$= 26.6 \text{ BTU loss per sq. ft. of outside surface of the covering per hour.}$$

From Fig. 6, 26.6 BTU surface radiation takes place at a temperature difference of 13 deg. between the surface and the surrounding air.

Therefore

$13^\circ + 80^\circ = 93^\circ$ instead of 100° which was assumed.

Substituting again for trial solution, using 93° for t_3,

$$103.2 - .293\, t_2 = .607\, t_2 - .607 \times 93$$

$$t_2 = 177^\circ$$

Then

$$H = 607 \times 177 - .607 \times 93$$

$$= 50.8 \text{ BTU loss per sq. ft. of pipe per hour.}$$

$$H_s = 50.8 \times \frac{4.3125}{8.3125}$$

$$= 26.4 \text{ BTU loss per sq. ft. of outside surface of the covering per hour.}$$

From Figure 6 a radiation of 26.4 BTU/sq. ft. of surface per hour takes place at a temperature difference of 13.6 deg. This added to the room temperature will give $t_3 = 93.6$ deg. which is practically as assumed in the second trial.

Therefore the radiation per sq. ft. of pipe would be 50.8 BTU per hour through graded covering consisting of 1″ magnesia and 1″ air cell.

Economic Conclusions

In order to eliminate the necessity for the use of involved calculations for those not interested in the mathematical solution for heat loss through graded pipe coverings, charts Fig. 10 and Fig. 11 have been prepared to give the results for 5″ pipe. Fig. 10 gives comparative values of heat loss for different kinds and combinations of coverings. A study of this chart discloses the fact that a graded combination of sponge felt and asbestocel is more efficient than magnesia and air cell at a temperature difference below 265 degrees while above that temperature the reverse is true. A comparison between dollars loss per lineal foot per year for any covering and the loss per year for the same pipe bare, Fig. 7, will show the amount saved by the covering selected.

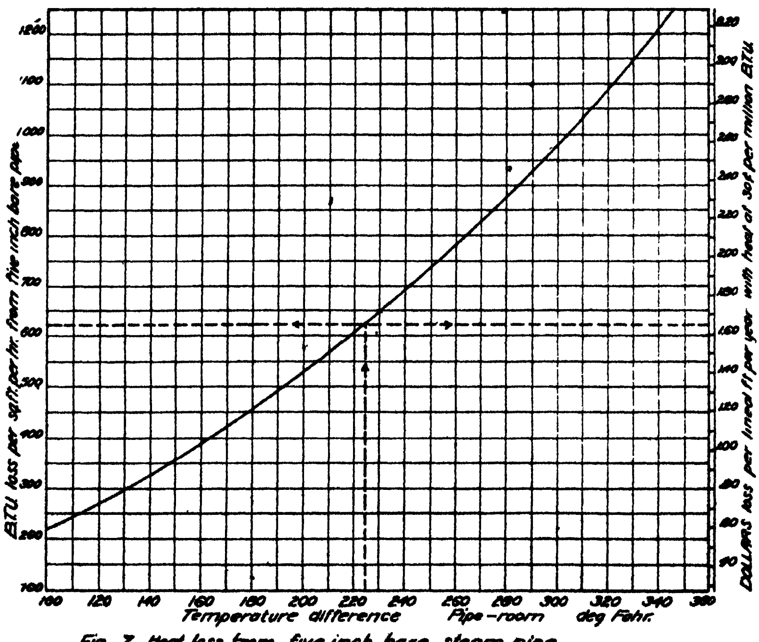

Fig. 7. Heat loss from five inch bare steam pipe.

Fig. 11 shows the saving in dollars per lineal foot per year due to adding either of three different coverings over a covering of 1″ magnesia already in place on a 5″ pipe. In addition, it also

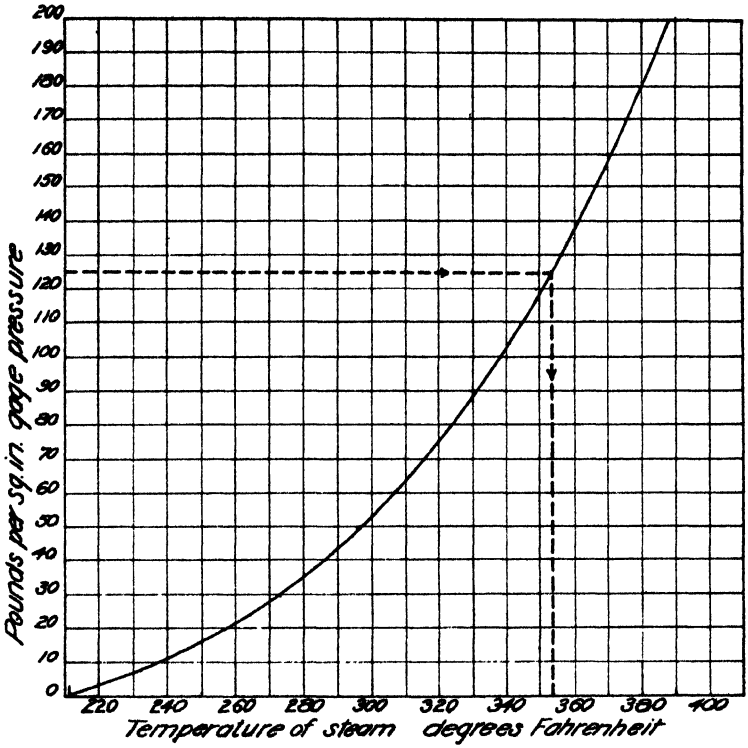

Fig. 8. Pressure-temperature curve for saturated steam.

shows the annual cost of single thickness coverings large enough to go over the covering already in place. This annual cost is computed on the basis of list price, at discounts up to 60% off, plus 10% of list price for erecting; assuming 6% interest on total first cost, and 5% of total first cost for upkeep, etc. The basis for computing the sinking fund annuity is 6%.

As an illustration in the use of the chart, a given installation of 5" pipe is carrying 125 lbs. of steam and is covered with 1" magnesia. Room temperature is 80 degrees. Examples are given where the investment is to be returned in 14, 20 and 30 years. Market prices of covering are assumed to be as shown in the following table for one lineal foot of covering.

Kind of Covering	Life Assumed	Price Assumed	Cost Per Year	Total Savings Per Lineal Ft. Per Year	Net Savings Per Year	Net Savings in Per Cent of Annual Cost
1¼" Magnesia	14 years	12% off	.154	.156	.002	1.29%
1" Asbestocel	14 years	35% off	.118	.129	.011	9.30%
1" Aircell	14 years	55% off	.086	.106	.020	23.30%
1¼" Magnesia	20 years	12% off	.133	.156	.023	1.71%
1" Asbestocel	20 years	35% off	.102	.129	.027	26.50%
1" Aircell	20 years	55% off	.075	.106	.031	41.30%
1¼" Magnesia	30 years	12% off	.120	.156	.036	3.00%
1" Asbestocel	30 years	35% off	.092	.129	.037	40.20%
1" Aircell	30 years	55% off	.068	.106	.038	56.00%

In the three cases cited above, the greatest total annual saving would accrue from using magnesia. However, air-cell, the most inexpensive covering of the three types considered, will show the greatest per cent return on the annual cost.

If the life of the covering, instead of a certain number of years is made the basis of the yearly cost, the above table will suggest some possible conclusions. For instance, assume the life of one covering as 14 years, another as 20 years, and the third as 30 years.

These examples will show the use to which this chart, Fig. 11, can be put for determining what type of covering it is most profitable to apply under given conditions.

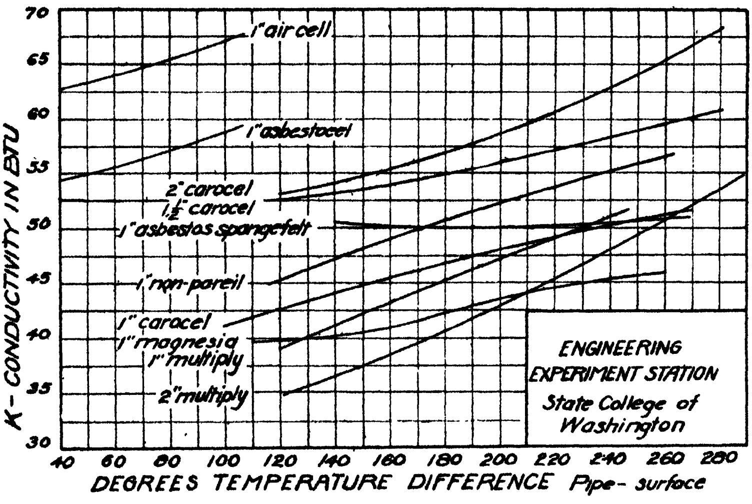

Fig. 9. Values of conductivity "K" for sample coverings

Approximate Heat Loss From Coverings Already Installed

Figure 12 is a chart for the purpose of determining the approximate radiation from a given installation of pipe covering already in operation, without the necessity of knowing the steam pipe temperature or kind of covering in use or its condition. The outside diameter of the covering is easily obtainable and the air temperature can be measured in the ordinary way with a mercury thermometer.

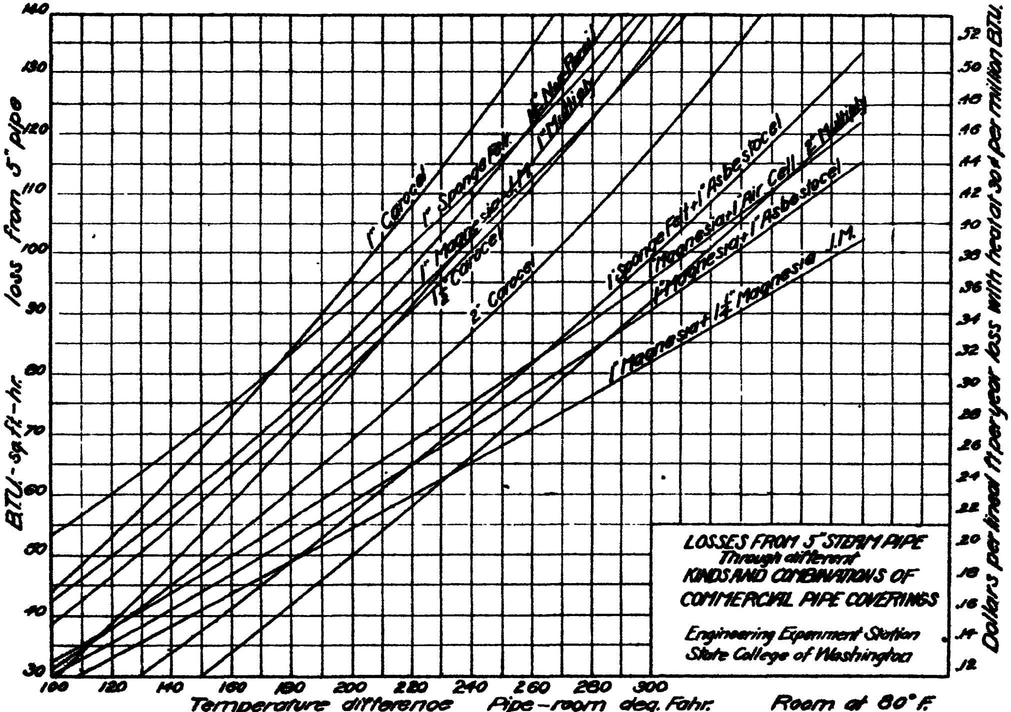

Fig. 10. Heat losses through samples of steam pipe coverings.

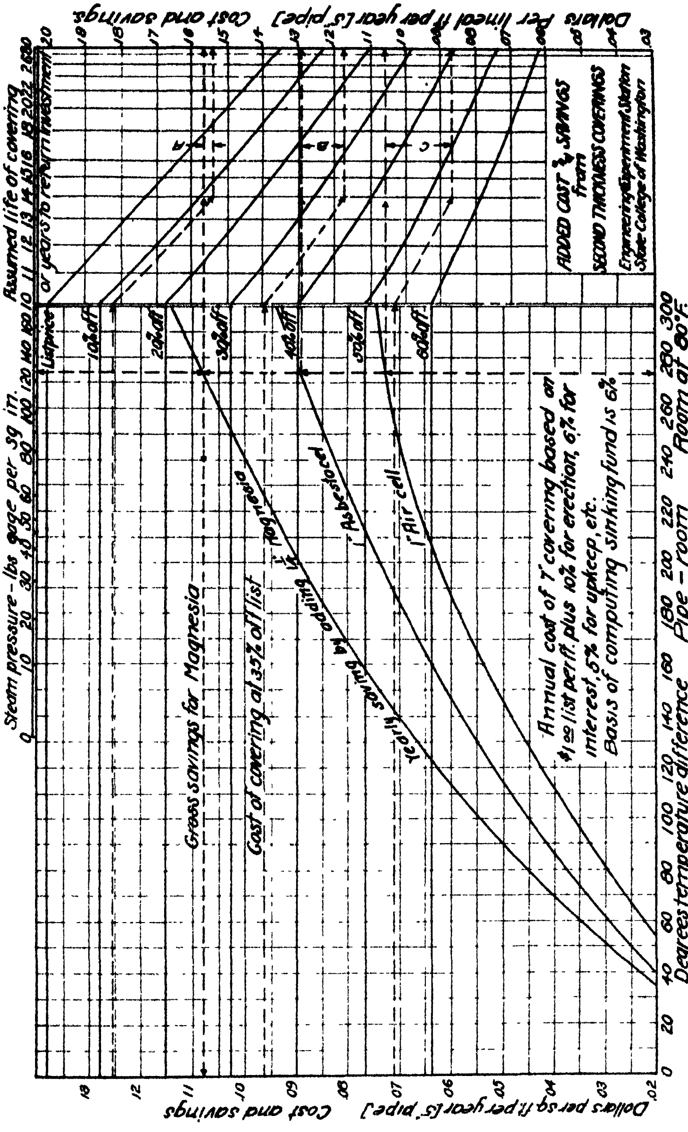

Fig. 11 Economic value of second thickness of covering on 5" steam pipe

The surface temperature is measured by means of a thermometer bound to the side of the covering with the bulb under a single thickness of three ounce canvas. Then the temperature difference between covering surface and air, applied to the chart for the outside diameter of the covering investigated will give the approximate radiation losses in BTU per hour or dollars per year per lineal foot. A series of tests of the above method of measuring surface temperatures of pipe covering gave an average variation of about 1¾ % higher than the temperature as determined by thermo-couples. The maximum variations never exceeded 3% higher.

Tin Jacketed Coverings

It is commonly known that at a given temperature a smooth bright surface such as tin will radiate less heat than would be radiated from a surface of canvas or of asbestos paper. This fact suggested a further possible heat saving in the insulation of steam pipes by the substitution of a polished tin surface for the usual canvas jacket on the outside of the covering. Such a test was made by measuring the heat loss through a high grade 1″ asbestos covering. Then a jacket of bright tin was tightly fitted over the surface of the covering and the heat loss was again measured for the same pipe temperatures. The saving in heat due to the addition of the tin surface is shown in the following table where the air temperature is at 80 deg. Fahr.

Pipe Temp.	Steam Pressure	BTU Heat Loss*		Per Cent Saved	Saving Per 100 Sq. Ft Per Yr. at 70c Per Million BTU
		Canves Surface	Tin Surface		
249	15	13.6	10.7	21.3	$1.78
276½	34	17.3	14.0	21.3	2.33
294½	48	20.4	16.1	21.1	2.63
312½	67	23.1	18.1	21.6	3.06
330	89	26.1	20.2	22.6	3.62
350	126	30.4	23.5	22.7	4.23

The above table will indicate that the saving is large enough to warrant serious consideration. Ordinary coke I C tin costs approx-

* BTU per hour per square foot of outer surface.

imately $18.00 per 100 sheets of a total area of 388 sq. ft. Allowing for lapping joints, 100 sheets will cover approximately 350 sq. ft., and, for example, allowing $17.00 for erecting, the total cost for tin jacketing the covering of a plant would be 10c per sq. ft. For pipes operating at a steam pressure, for instance, of 126 lbs. per sq. inch the saving would be 4.2c per sq. ft., or an interest on the investment of 42%. It has been assumed that only straight runs of pipe will be covered with tin and that no attempt will be made to make it water tight.

It should be noted in considering a tin covering that the tin jacket affords considerable protection to the covering and justifies a reduction in the sum set aside for maintenance and depreciation on the covering. The tin, in certain cases, may also replace the canvas jacket now used on insulating coverings.

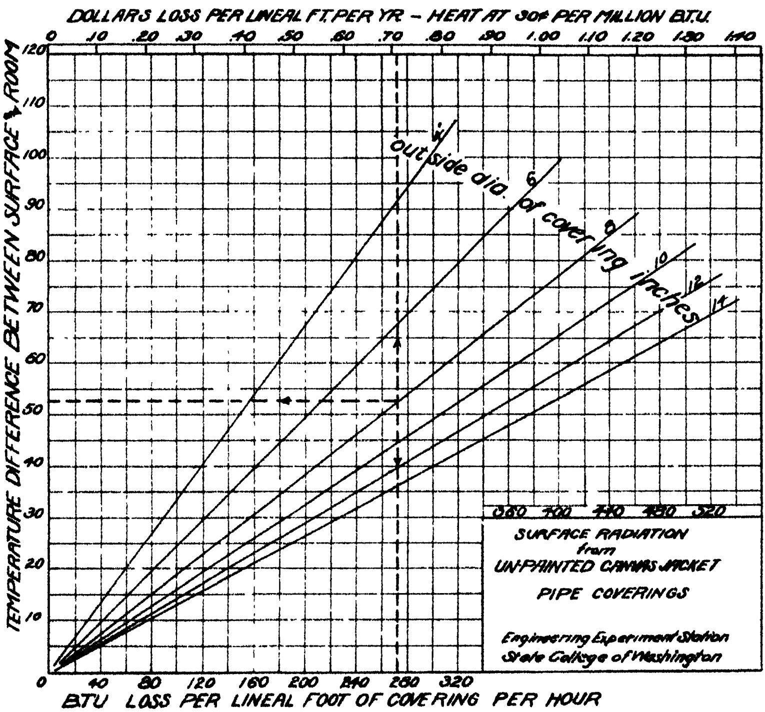

Fig. 12. Economic losses from pipe coverings determined from surface and air temperatures and external diameter of the covering.

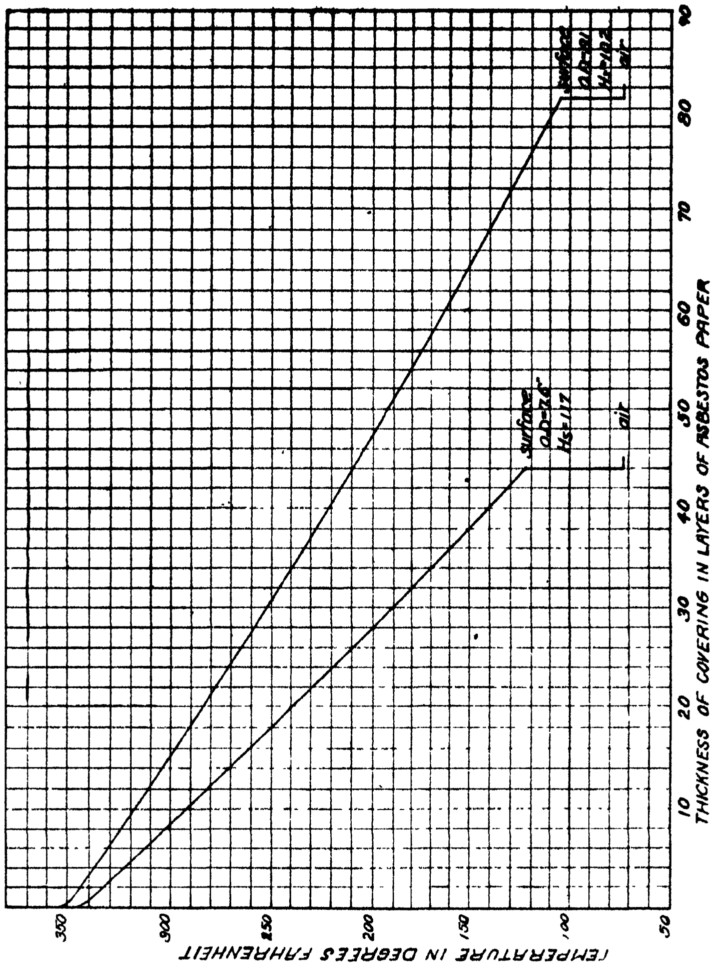

Fig 13. Temperature gradient for asbestos sponge felt pipe covering

Sample Calculation of Heat Loss From a Domestic Hot Water Heating System

In computing the heat losses from the pipes of a domestic hot water system, the temperatures used are comparatively low—approximately 160 to 200 degrees Fahr.—and the temperature difference between a covering surface and room temperature would be small.

At such temperatures the heat loss is but little more from the cheapest covering than from the most expensive. For this reason, domestic hot water systems are usually insulated with but one thickness of air cell or similar grade covering. The furnace boiler itself is usually covered with plastic magnesia.

A certain amount of radiation in the basement is usually desirable because a house is much better for children and easier to keep comfortable if the floor is not cold. Radiation from pipes covered with one inch of covering will usually warm the basement enough to prevent freezing. Exposed pipes would keep the basement air much warmer.

Following is a sample calculation for the heat losses from a domestic heating plant, first with pipes exposed and then comparing the use of each of two different grades of covering such as 1″ magnesia and 1″ aircell. The calculation is applied to a 4″ pipe in a basement free from cold air drafts.

Pipe temperature = 180 degrees.

Air temperature, = 70 degrees.

Hours in service, (8 mo per year) =5760

Bare pipe losses per hr. = 244.2 BTU per sq. ft. of pipe.

Bare pipe losses per eight mo. = 1,405,000 BTU per sq. ft.

Heat costs approximately $1.00 per million BTU.

(High because of low average furnace efficiency)

Total loss per sq. ft. per eight mo. = $1.405.

Calculated Loss Per Sq. Ft. of 4″ Pipe Covered With 1″ Covering

Outside diam. 4″ pipe = 4.5″, rad. = 2.25″ $\log_e 2.25 = .8109$

Outside diam. 1″ cov. = 6.5″, rad. = 3.25″ $\log 3.25 = 1.1787$

$$H = \frac{k\,(t_1 - t_2)}{r(\log_e r_2 - \log_e r_1)}$$

One inch magnesia:

k_1 mag $= .40$
$t_1 = 180^\circ$
$t_2 = 91^\circ$ ave.

$$H = \frac{.40(180 - 91)}{2.25(1.1787 - .8109)}$$

=43.2 BTU per sq. ft. per hr

Total loss per sq. ft. per yr

$5760 \times 43.2 \times .0001 = 24.9c$

Cost 1" Magnesia, list=50.9c per sq. ft. of pipe surface.

At 10% off list=45.8c per sq. ft.

One inch air cell:

k_1 air cell $= .50$
$t_1 = 180^\circ$
$t_2 = 96^\circ$ ave.

$$H = \frac{.50(180 - 96)}{2.25(1.1787 - .8109)}$$

=50.8 BTU per sq. ft. per hr.

Total loss per sq. ft. per yr.

$5760 \times 50.8 \times .0001 = 29.3c$

Cost 1" Aircell, list, =50.9c per sq. ft. of pipe surface

At 45% off list =28.1c per sq. ft.

Difference in savings in favor of magnesia = 4.4c per sq. ft. per year.

Difference in first cost in favor of air cell = 17.7c per sq. ft.

Value of heat saved by one inch air cell = 140.5 — 29.3c = 111.2c, or $1.11, per sq. ft. per year.

This shows that even here high grade covering pays a good return upon its extra cost. Usually however, the heat lost through the cheaper covering is no more than is desired to keep the basement fairly warm.

BIBLIOGRAPHY

Pipe Coverings

Books

American Society of Mechanical Engineers. Transactions

Vol. 16 p.827 (646) 1894-1895.

Vol. 23 p. 791, 952, 1901-1902.

Vol. 27 p.921, 1514, 1915-1916.

Armstrong Cork Co. Nonpareil corkboard insulation, '17.

Armstrong Cork Co. Nonpareil high pressure coverings, '11.

Baldwin, W. J. Baldwin on heating. 16 ed. rev. & enl. 1908, p.339-344.

Carpenter, R. C. Heating & ventilating buildings, 2nd ed. rev. 1897. p. 197-200, 228-230.

Franklin manufacturing company. Magnesia coverings.

Gebhardt, G. F. Steam power plant engineering. 3rd ed. 1912. p. 615-619; p. 691-693.

Harding & Willards Mechanical Equipment of Buildings, Vol. I, pp. 514-581.

Houstoun, R. A. Introduction to mathematical physics. 1912. p. 87.

Machinery's Encyclopedia, v.3, p.542-3. Heat insulating material.

Machinery's handbook. 1919. p.1277-8.

Marks, L. S. Mechanical engineers' handbook. 1916. p.308, 840-841.

National tube company. National pipe standards. 1917. p.348-350

Paulding, C. P. Practical laws and data on condensation of steam in covered and bare pipes. 1904. p.87.

Standard handbook for electrical engineers. 3d ed. 1910. sec. 10, 387.

Union fibre co. Insulation of railway equipment. '12.

U. S. Bureau of Mines. Technical paper 114, by H. Kreisinger.

U. S. Bureau Standards Circular. 55.58-9 '15

Allen, J. R. and Walker, J. H. Heating and Ventilation. 2d ed. McGraw, 1922.

Johnson, J. W. New handy manual on heating, ventilating and mechanical refrigeration. 11th ed. Caspar, 1921.

Raynes, F. W. Heating systems. 2d ed. Longmans, 1921.

Royds, R. Heat transmission in boilers, condensers and evaporators. Van Nostrand, 1921.

Royds, R. Heat transmission by radiation, conduction and convection. Van Nostrand, 1921.

U. S. Bureau of Mines. Technical paper 217. Saving coal in steam power plants. Reprint of Engineering bulletin no. 2. U. S. Fuel Administration. 1919.

U. S. Bureau of Mines. Technical paper 221. Saving steam in industrial heating systems. Reprint of Engineering bulletin no. 6. U. S. Fuel Administration. 1919.

Magazines

Am. Inst. of Min. Engrs. Bulletin Aug. & Dec. 1915. P. A. Boeek.

Am. Inst Min. E. Bul. 104:15 39-50 Ag '15. P. A. Boeek.

Am. Soc. Ht. & Vt. Engrs. Jl-Jan '17. G. B. Nichols.

Am. Soc. M. E. J. Dec. 1915. L. B. McMillan.

Am. Soc. M. E. J. 38:8-16 Ja '16. 38-140-2F '16. L. B. McMillan.

Am. Soc. M. E. J. 38:98-9 Ja. '16 or Metal Work 85:284 F 25, '16, L. B. McMillan.

Am. Soc. M. E. J. Jl-Aug 1916. P. A. Boeek.

Am. Soc. M. E. J. 40:918-23 N 18. G. D. Bagley.

Coal Age 13:692-3 Ap 13, '18

Concrete 12: sup 20 F '18 or Am. Gas Eng J 108:52 Ja 19, '18, W. F. Schaphorst.

Dom Eng 72:252-3 Ag 28, '15. C. L. Hubbard.

Dom Eng 85:320-2 N 30, '18. A. G. King.

Elec. R 73:1018 D 28, '18 Coal.

Elec W 70:671-2 O 6 '17.

Elec W 71:554-6 Mar 16, '18.

Elec W 71:1377 Je 29 '18.

Elec W 72:215 Ag 3, '18. R. B. Fehr.

Eng & Min J 95:619 Mr 22, '13. R. K. Stockwell

Eng & Min J 95:805-6 Ap 19 '13.

Engineering (Lond) Sept 22, 1911.

Eng. N 70:1083 N 27, '13.

Eng. N 73:878-9 My t, '15

Factory 21:904 N '18

Gas Age 40:162 Ag 15, '17 W. F. Schaphorst.

Gas Age 42:113 Ag 15, '18 G. D. Bagley

Heat & Ven 10:31-3 May '13.

Heat & Ven 10:42-3 Jl '13.

Heat & Ven 10:48-9 F '13

Heat & Ven 13:11-18 My '16

Iron Age 97:1122-3 My r, '16

Iron Tr R 59:1004-6 N 16, '16

Met & Chem Eng 13:129 F '15

Met & Chem Eng 13:315 My '15 or Eng M 49:415 Je '15

Met & Chem Eng 14:551-2 My 1, '16

Met & Chem Eng 16:109 Ja 15 '17

Metal Work 82:794-6 D18 '14

Metal Work 83:356 Mr 5, '15

Metal Work 85:712-13 My 26, '16

Metal Work 86:185 Ag 11 '16

Metal Work 88:660 N 30 '17

Metal Work 88:747, 773 D 21-28, '17

Metal Work 82:159-61 F 1, '18

Power 37:862-Je 17, '13

Power 42:426-7 S 21, '15.

Power 43:491 Ap 4 '16.

Power 43:248-9 F 22, '16

Power 43:491 Ap 4 '16

Power 43:621-2 My 2, '16

Power 44:820, 45:568 D 12-16, Ap 24 '17.

Power 45:593-6 My 1, '17; 47:484 Ap 2, '18.

Power 47:742 My 21 '18, 47:924 Je 25, '18.

Power 48:626 O 29, '18.

Power 48:814 D 3 '18.

Sci Am 117:349 N 10, '17

Sci Am 118:499 Je 1, '18.

Sci Am S 87:373 Je 14, '19.

Wis Eng Nov 1914.

Am. Arch 118:648-52 N 7, '20.

Am Soc Heat & V E J, 26:455-69, 588-96 My, S '20, 26:569-74 Jl '20.

Am Soc Heat & V E J 26:625-52 O, '20

Am Soc Heat & V E J 26:sup I-XIX S, '20, Ill U Eng Exp Sta Bul 117:1-31, '20.

Am Soc Heat & V E J 27:690-2 S, '21.

Blast F & Steel Pl 8:259-61 Ap, '20.

Blast F & Steel Pl 10:261-5 My, '22, Same, Chem & Met Eng 27:63-5 Jl 12 '22.

Chem & Met Eng 23:1158-60 D 15, '20.

Chem & Met Eng 24:295-300 F 16, '21, Heat & Ven 18:30-4 F; 32-4 Mr, '21.

Chem & Met Eng 24:388 Mr 2, '21.

Dom Eng 93:5-7, 59-61, O 2-9, '20.

Engineer 129:73 Ja 16, '20, Power 51:280 F 17, '20.

Engineering 114:155 Ag 4, '22.

Eng. & Ind Management 6:115 Ag 4, '21.

Eng & Ind Management 6:720-2, 7:39-41 D 22, '21, Ja 12, '22.

Heat & Ven 18:30-34 F, '21.

Heat & Ven 18:64-5 Ja, 66-9 F, '21.

Heat & Ven 19:45 Mr, '22.

Ice & Refrigeration 59:82-4 S, '20.

J Am Ceramic Soc. 3:865-74, 874-6 N, '20.

Mech Eng 42:230-2 Ap, '20; Am Soc Heat & V E J 26:445-533 My, '20; Am Soc Heat & V E J 26:549-54 Jl, '20.

Plumber 94:487 N 5, '20.

Power 53:787-8 My 17, '21.

Power 54:419-20 S 13, '21.

Power 55:747 My 9, '22.

Power 56:318-19 Ag 29, '22.

Power 56:354-7 S 5, '22.

Power Pl Eng 24:514-6 My 15, '20.

Power Pl Eng 24:740-3 Ag, '20.

Power Pl Eng 24:808 Ag 15, '20.

Power Pl Eng 24:983-4 O 15, '20.

Power Pl Eng 25:285-6 Mr 1, '21.

Power Pl Eng 25:629 Je 15, '21.

Power Pl Eng 25:897 S 15, '21.

Ry Mech Eng 93:711-12 D, '19.

Sanitary & Heat Eng 98:250-3 N 3, '22.

Sheet Metal Worker 11:245-6 O 1, '20.

Sheet Metal Worker 11:372-3 N 26, '20.

Textile World 62:735 Ag 5, '22.

LIST OF ILLUSTRATIONS

ENGINEERING BULLETINS PUBLISHED BY THE STATE COLLEGE OF WASHINGTON ENGINEERING EXPERIMENT STATION.

1. Sewage Disposal for the Country Home.
   By O. L. Waller and M. K. Snyder. Mar 1914, July, 1916 (Out of print).

2. How to Measure Water.
   By O. L. Waller. Oct. 1915.

3 Water Supply for the Country Home.
   By M. K Snyder. (Out of print)

4. Construction and Maintenance of Earth Roads
   By L. V. Edwards. April 1916.

5. Cost of Pumping for Irrigation
   By O. L. Waller. Aug., 1916.

6 Fuel Economy in Domestic Heating and Cooking
   By B. L. Steele. Dec., 1917.

7. Thawing Frozen Water Pipes Electrically.
   By H. J. Dana. Oct. 1921.

8 The Use of Ropes and Tackle.
   By H. J. Dana and W A Pearl. Dec. 1921.

9. Well and Spring Protection.
   By M. K. Snyder Jan. 1921

10 Water Purification for the Country Home.
   By M. K. Snyder. Feb 1922.

11. Water Supply Systems for the Country Home.
   By M. K. Snyder and H. J. Dana. July 1922.

12. Commercial Efficiency of Graded Steam Pipe Coverings.
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   By Wm. A. Pearl and Eri B. Parker. Feb. 1923.

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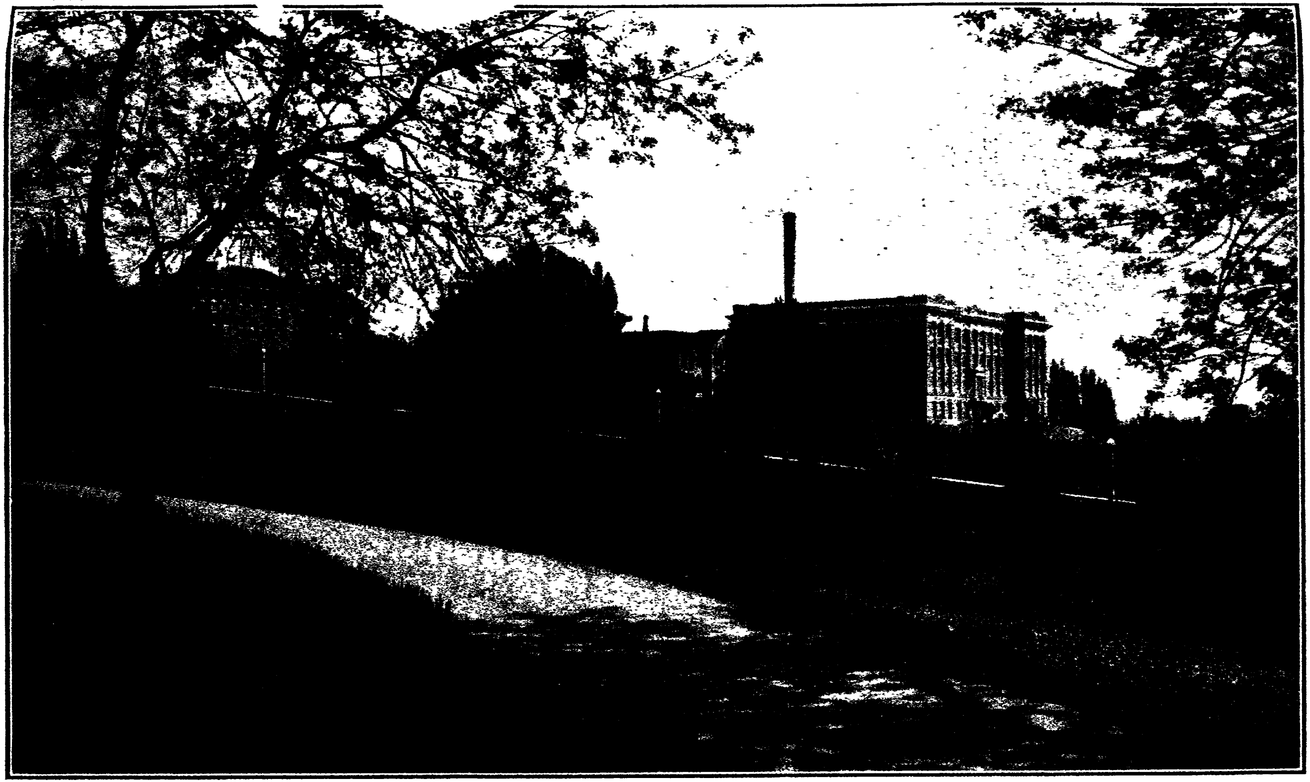

ENGINEERING BUILDINGS, ENGINEERING EXPERIMENT STATION

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 5 February, 1923 Number 9

Critical Velocity of Steam
With
Counter-Flowing Condensate

By Wm. A. Pearl and
Eri B. Parker

ENGINEERING BULLETIN No. 13

Engineering Experiment Station
H. V. CARPENTER, Director

1923

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instuments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors ,etc.

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When this experiment was started, no material on the subject was found. During the process of the work two articles briefly stating the results of similar experiments covering a part of this work were published.

One article written by F. E. Gieseke, Head of the Research Division of the University of Texas, was presented at a semi-annual meeting of the American Society of Heating and Ventilating Engineers at Buffalo-Detroit in June, 1922.

The other tests were carried on at the laboratories of Warren Webster and Company and the results appeared in their last edition of "Steam Heating."

CRITICAL VELOCITY OF STEAM WITH COUNTER-FLOWING CONDENSATE

Object

In any installation, such as a one-pipe heating system or any other arrangement wherein it is desirable to carry the condensate back through the same pipe, it would be advantageous to know the critical velocity of the steam. By Critical Velocity, is meant the maximum flow of steam that can be maintained without hindering the continuous return of the condensate.

The lack of accurate information on this subject has caused such installations to be based almost entirely upon the judgment and the experience of the designer. It can easily be seen that such practice might lead to extravagant habits in design in order to insure the proper working as well as to protect the designers' reputation.

Authors of text books on the subject of heating have been unable to give accurate data on this phase of the work but have contented themselves with giving what they considered safe practice.

The object of this research is to study the conditions existing in one-pipe systems and to arrive at some conclusions that will be useful in any designs requiring a counter-flowing condensate.

Method and Apparatus

The method of approaching this problem was to set up a typical single pipe heating installation and to observe the effect of varying conditions of velocity, pipe-size, slope, and pressure upon the uniform return of the condensate. Steam of a known pressure and uniform quality was conducted through a pipe of known size

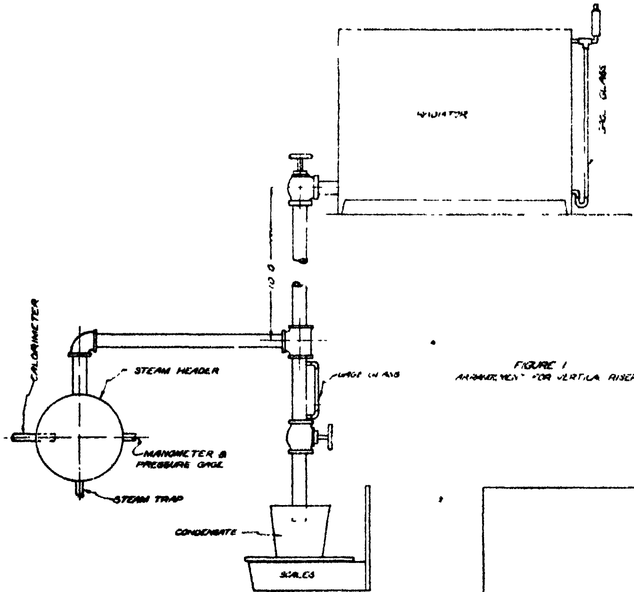

FIGURE 1
ARRANGEMENT FOR VERTICAL RISER

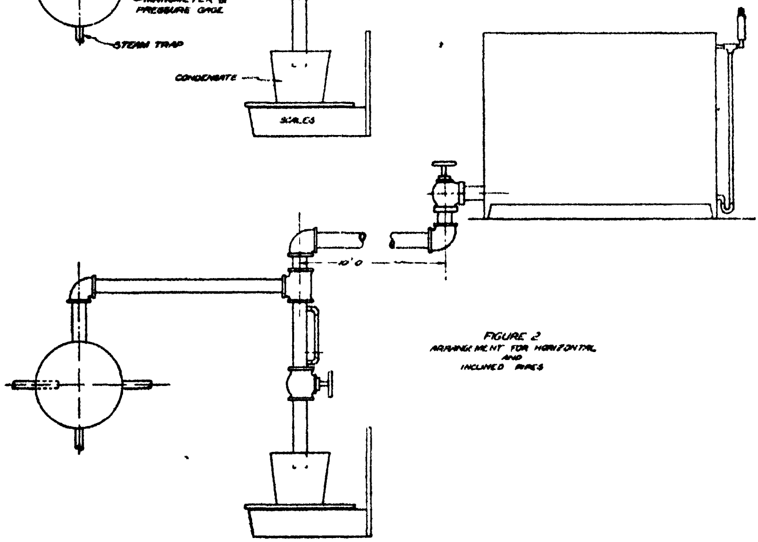

FIGURE 2
ARRANGEMENT FOR HORIZONTAL
AND
INCLINED PIPES

and pitch to a radiator of suitable size and the counter flow of the condensate observed under varying conditions of velocity.

By referring to the accompanying plates, figures 1 and 2, the following description of apparatus used may be more clearly understood.

Steam for the experiment was led into a header that was made up of a four foot section of six inch pipe. The header was provided with a manometer, pressure gage, steam trap, and suitable connections for a calorimeter. Dry saturated steam was led from the top of the header to an ordinary radiator. Figure 1 shows the arrangement of pipes for the tests on vertical risers The riser in each case was a ten foot length of pipe with standard radiator valve and connections. The radiator was fitted with a water glass and air valve as shown. Figure 2 shows the connections for horizontal pipes. The slope was varied by raising the radiator.

The radiation was varied by a number of different methods, by use of coverings, by use of a variable speed fan, and by the use of water.

DATA

The first data were taken with a vertical riser and a standard valve of the same nominal size. Readings were taken for each pipe size under pressures of considerable range.

Tests of ten minutes duration were run during which time the pressure and rate of condensation was held constant. Working in this manner, the rate of condensation was gradually increased until a point was reached where the condensation did not all return in the pipe. The maximum amount returned was recorded.

The maximum amount of water returned was determined by carefully weighing the returned condensate for each ten minute test. Careful observation was made in each case to determine whether or not any water was held up. It was found that as the radiation was increased for each ten minute period, the condensate returned increased in proportion up to a certain point at which it showed a marked decrease. In each case, at this point, water was

found to have been held up in the radiator, which showed that the critical velocity had been exceeded.

Tests were run in this manner on vertical, inclined, and horizontal pipes, ranging in size from three-fourths inch to two inches inclusive, and under pressures ranging from one to six pounds.

The first thing of importance noted was that the critical velocity was practically independent of the pressure used. This is shown in table 1, in which it may be noted that the maximum condensate returned in each ten minute period was practically constant.

This condition being established no further reference to pressure will be made in the following discussion.

In making calculations for critical velocities, table 2 was made up. The values for maximum condensate returned, as shown in this table, are the average values for each pipe size as shown in table 1.

During the test it was observed that the maximum condensate was not necessarily governed by the pipe size, but rather by the smallest cross-section in the line through which the condensate must flow.

As a result of this, when a standard valve for the pipe used was installed, it became the governing factor because of the smaller throat area.

With the elimination of this condition in view, a series of tests were run in which the valve used was one size larger than the pipe. In this case the pipe became the limiting factor instead of the valve. (See table 3).

Because of this condition where valves of the same nominal size as the pipe are used, two different critical velocities may be calculated. The value obtained by using the area of the pipe will be a false value and should not be considered since the velocity through the valve is the velocity that actually limits the flow.

By using a valve one size larger than the pipe, the true critical velocity in the pipe was determined and these values are shown in table 3.

TABLE 1

CRITICAL VALUES

PIPE SIZE	PRESSURE	VERTICAL	SLOPE ½ IN in 10 Feet	SLOPE 6 IN. in 10 Feet
		Condensate Return in 10 Minutes	Condensate Return in 10 Minutes	Condensate Return in 10 Minutes
¾″	1 lb.	..... lbs.	.937 lbs.	1.562 lbs.
¾″	2 lbs.	1.437 lbs.	1.000 lbs.	..... lbs.
¾″	3 lbs.	..... lbs.	.875 lbs.	1.312 lbs.
¾″	4 lbs.	1.500 lbs.	.937 lbs.	..... lbs.
¾″	5 lbs.	1.375 lbs.	.937 lbs.	1.312 lbs.
¾″	6 lbs.	1.325 lbs.	1.000 lbs.	1.500 lbs.
1″	1 lb.	3.312 lbs.	2.000 lbs.	..... lbs.
1″	2 lbs.	3.218 lbs.	2.125 lbs.	3.687 lbs.
1″	3 lbs.	..... lbs.	1.887 lbs.	..... lbs.
1″	4 lbs	.... lbs.	1.875 lbs.	..... lbs.
1″	5 lbs.	3.187 lbs.	..... lbs.	..... lbs.
1″	6 lbs.	3.375 lbs.	1.812 lbs.	..... lbs.
1¼″	1 lb.	5.687 lbs.	4.437 lbs.	5.620 lbs.
1¼″	2 lbs.	5.250 lbs	4.500 lbs.	6.125 lbs.
1¼″	3 lbs.	5.000 lbs	5.000 lbs.	5.625 lbs.
1¼″	4 lbs.	5.375 lbs.	4.750 lbs.	5.625 lbs.
1¼″	5 lbs.	5.437 lbs	4.687 lbs.	6.000 lbs.
1¼″	6 lbs.	5.750 lbs.	..... lbs.	5.875 lbs.

Although the values shown above vary somewhat, apparently no relation exists between pressure and critical velocity. These values are single readings and the variation is apparently due to irregularity of flow of the condensate at the critical point and to the short duration of each test.

As a result of this unavoidable condition the values used in the final calculations and charts are the averages of a number of readings in each case. Approximately two hundred readings were taken on each pipe size.

TABLE 2

VELOCITY IN PIPES AND VALVES

	Nominal Pipe Size	Nominal Valve Size	Actual Pipe Size	Actual Diam. of Valve Throat	Actual Pipe Area	Actual Valve Area	Pounds Per Minute	Volume Per Minute**	Velocity Ft. per Minute in Pipe*	Velocity in Valve Ft. per Minute	B. T. U. Per Min.***
Slope ½" in 10 Feet	¾ inch	¾ inch	13-16 inch	¾ inch	.5184	442	.0948	2.13	592	694	92
	1 inch	1 inch	1 3-64 inch	1 inch	8600	.785	.1979	4.45	745	816	192
	1¼ inch	1¼ inch	1 3-8 inch	1¼ inch	1.485	1.227	.4604	10.33	1002	1213	448
Slope 1½" in 10 Feet	¾ inch	¾ inch	13-16 inch	¾ inch	.5184	.442	.140	3.15	875	1025	136
	1 inch	1 inch	1 3-64 inch	1 inch	.8600	.785	.340	7.65	1282	1405	330
	1¼ inch	1¼ inch	1 3-8 inch	1¼ inch	1 485	1.227	.5875	13.22	1283	1552	572
Slope 6" in 10 Feet	¾ inch	¾ inch	13-16 inch	¾ inch	.5184	.442	.1448	3.255	903	1062	141
	1 inch	1 inch	1 3-64 inch	1 inch	8600	.785	.3687	8.30	1390	1522	357
	1¼ inch	1¼ inch	1 3-8 inch	1¼ inch	1.485	1.227	.5812	13.08	1270	1536	566
Slope 12" in 10 Feet	¾ inch	¾ inch	13-16 inch	¾ inch	.5184	.442	.1562	3.52	978	1145	152
	1 inch	1 inch	1 3-64 inch	1 inch	.8600	.785	.3625	8.15	1367	1495	353
	1¼ inch	1¼ inch	1 3-8 inch	1¼ inch	1 485	1.227	.6000	13.50	1310	1585	584
	1½ inch	1½ inch	1 39-64 inch	1½ inch	2.04	1.767	.8625	19.41	1375	1590	836
	2 inch	2 inch	2 1-16 inch	2 inch	3.341	3.141	1.525	34 30	1477	1573	1485
Slope 54" in 10 Feet	¾ inch	¾ inch	13-16 inch	¾ inch	.5184	..442	.1437	3.233	897	1052	139
Vertical	¾ inch	¾ inch	13-16 inch	¾ inch	5184	.442	.1416	3.1825	887	1038	137
	1 inch	1 inch	1 3-64 inch	1 inch	.8600	.785	.3313	7.45	1248	1370	322
	1¼ inch	1¼ inch	1 3-8 inch	1¼ inch	1 485	1.227	.5433	12.22	1185	1438	528

* This is not a true critical value for Pipe Velocity since the limit is in the valve

** Specific volume taken as 22.5 cu. ft per lb

*** B. T. U. per lb. taken as 970.

CRITICAL VELOCITY IN PIPE

TABLE 3

Slope 6 Inches in Ten Feet

Nominal Size	Actual Size	Actual Area	Lbs Per Minute	Volume in Cu Feet Per Minute	Velocity Feet Per Minute	B. T. U. Per Minute
¾ inch	13-16 in.	.5184	.1687	3.80	1052.	164.
1 inch	1 3-64 in.	.860	.4000	9.02	1505.	389.
1¼ inch	1 3-8 in.	1.485	.7500	16.88	1640.	730.
1½ inch	1 39-64 in.	2.04	1.025	23.10	1630.	1000.
2 inch	2 1-16 in.	3.341	1.568	35.3	1520.	1519.

* Using a valve one size larger than pipe

TABLE 4

Slope 6 Inches in Ten Feet

Nominal Size	Actual Size	Actual Area	Lbs Per Minute	Volume in Cu. Feet Per Minute	Velocity Feet Per Minute	B T U Per Minute
Velocity in ¾ inch pipe, using 1 inch valve						
¾ inch	13-16 in.	.5184	.1687	3.80	1052.	164.
Velocity in ¾ inch valve fed by ¾ inch pipe						
¾ inch	¾ -in.	.44	.1448	3.26	1056.	141.
Velocity in ¾ inch valve fed by 1 inch pipe						
¾ inch	¾ -in.	.44	.1687	3.78	1231.	164.
Velocity in ¾ inch orifice set in 1 inch pipe						
¾ inch	-.781 in	.48	.200	4.5	1350.	194.5

It is interesting to compare the critical velocity found in the pipe as shown in table 3 with the values for the valve in table 2. These values compare as consistently as could be expected considering the slight difference in size(for it will be noted from both tables that the critical velocity increases slightly with the pipe size within certain limits).

In order to further check the evidence that the critical velocity is determined by the smallest area in the line, tests were run on a one inch pipe with a three-fourths inch orifice in a thin metal plate inserted in the line.

Tests were also run on a one inch pipe with a three-fourths inch valve. The results of these tests are shown in table 4.

A comparison of these values shows that although the critical velocity in the line is governed by its smallest cross-sections, if this smallest section is an orifice or valve opening, it does not have quite as much effect on the critical velocity as a longer section would have.

RESULTS

The results of these observations may be summarized as follows:

A. The critical velocity of steam in a one pipe heating system is independent of pressure within ordinary heating ranges

B. The critical velocity increases slightly with an increase in pipe size. This increase is greater in smaller pipe sizes and becomes practically negligible in sizes larger than 1¼ inches. This is shown from values given in table 3 and velocities thru valves in table 2.

C. Referring to table 2, it will be seen that the critical velocity increases with an increase in slope up to 1½ inches in 10 feet. For greater slopes than this the critical velocity shows practically no increase. For vertical risers the velocity even shows a slight decrease from that of the 1½ inch slope. (See figure 3.)

D. The standard valves as used in heating practice have an actual throat area smaller than the actual area of the pipe of the same nominal size. As a result of this condition the capacity of

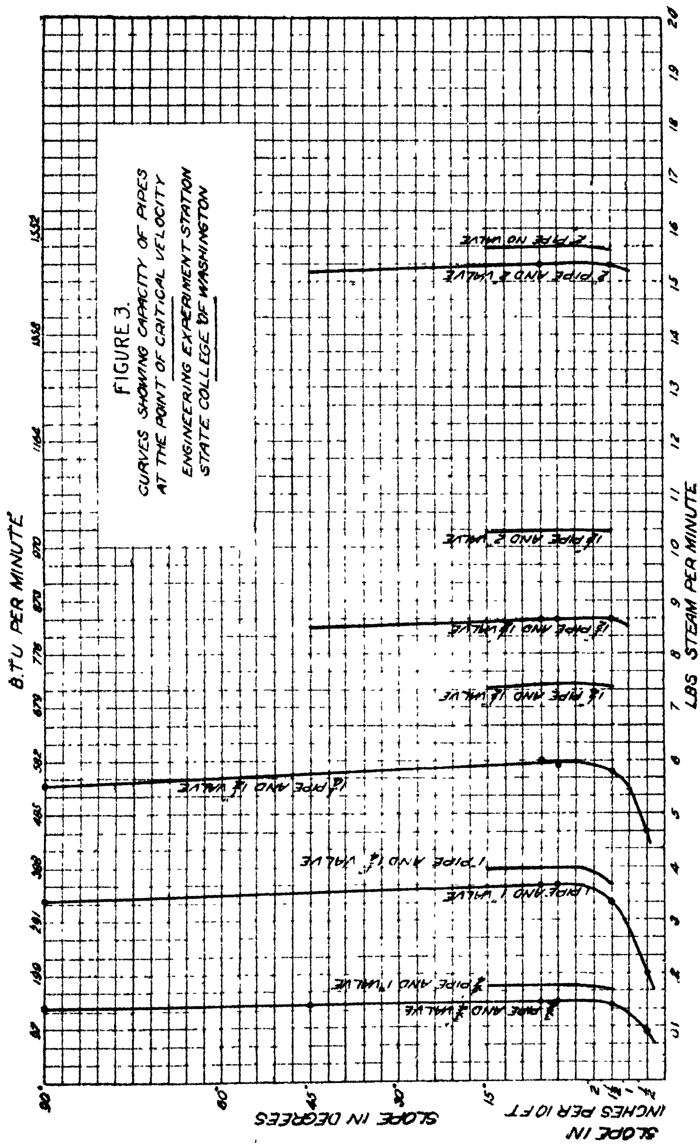
FIGURE 3.
CURVES SHOWING CAPACITY OF PIPES
AT THE POINT OF CRITICAL VELOCITY
ENGINEERING EXPERIMENT STATION
STATE COLLEGE OF WASHINGTON
B.T.U PER MINUTE
LBS STEAM PER MINUTE
SLOPE IN DEGREES
SLOPE IN INCHES PER 10 FT.
2" PIPE NO VALVE
2" PIPE AND 2" VALVE
1½" PIPE AND 2" VALVE
1½" PIPE AND 1½" VALVE
1¼" PIPE AND 1½" VALVE
1¼" PIPE AND 1¼" VALVE
1" PIPE AND 1¼" VALVE
1" PIPE AND 1" VALVE
¾" PIPE AND 1" VALVE
¾" PIPE AND ¾" VALVE

the runout is limited by the valve. Data showing this comparison with an explanation are given in table 5.

E. As long as the critical velocity is exceeded in the runout, the amount of water held up in the radiator will continue to increase even though a considerable head is produced. By tests it was found that by exceeding the critical velocity for a sufficient time the radiator tends to fill with water. In connection with this, one test was run during which the critical velocity was greatly exceeded. The radiator completely filled with water and. in this condition, even though the flow of steam was practically reduced to zero, the entire head was maintained with no return in the pipe whatever. This condition shows what happens if a pipe is greatly overloaded with radiation in a one pipe heating system. If a pipe is slightly overloaded with radiation (that is, if the critical velocity is slightly exceeded) the returns become intermittent, and noisy operation may result.

F. With regard to the conditions that exist when steam is turned into a cold radiator, some interesting results were obtained. Steam was turned into a cold radiator which was of proper size to give critical velocities in the pipe under normal running conditions at the existing room temperature. A standard air valve was used. The test was run until the entire radiator became hot, at the end of which time the condensation was weighed. Careful observation during the test showed that except for the first rush of steam, the critical velocity was not exceeded, and no condensate was being held up in the radiator at the end of the warming-up period. This test shows that in so far as the heating of the radiator itself is concerned, no difficulty may be expected due to excessive velocities.

PRACTICAL APPLICATION

The practical applications of these observations briefly stated are:

As to pipe size:

A. Where noise is objectionable the critical velocity must not be exceeded at any time.

B. Where a certain amount of noise during the heating up period of the room is allowable the critical velocity might be exceeded slightly and sizes chosen for the normal heating conditions. Great care must be exercised if the latter method is used or unsatisfactory results will follow.

Experiments have shown that the heat emitted by a radiator increases about 6 per cent for each 10 degree decrease in room temperature from 70 degrees Fahr. As a result of this increase if the pipe size is chosen so as to give approximate critical velocity under normal room temperatures, the critical velocity will be exceeded during the heating up period of the room, and a noise may result. To eliminate this condition. if it is objectionable, the pipe size should be chosen to conform to maximum requirements during the heating up period of room. The following example will illustrate this condition:

Considering a 1¼ inch pipe with a slope of 1½ inches in 10 feet, the critical velocity was found to be 1552 ft. per minute which corresponds to a transmission of 575 B. T. U. per minute or 34,500 B. T. U. per hour. Assuming conditions such that 250 B. T. U. are radiated per square foot per hour with a room temperature of 70 degrees, it is found that 138 square feet of radiation would be allowable on the above pipe. If, however, the room temperature is dropped to 40 degrees Fahr., the radiation will now be increased 6 per cent for each 10 degree difference or 18 per cent for the total increase. This increases our radiation per square foot from 250 to 295 B. T. U. per hour which would give only 117 square feet of radiation allowable on the 1¼ inch pipe as compared with the 138 square feet calculated for a room temperature of 70 degrees Fahr.

C. Since a pipe with the same nominal size valve is limited by the valve one method of working a pipe to its limit is to install a valve one size larger than the pipe.

The following table might be profitably studied in connection with the design of a one pipe heating system.

TABLE 5

Slope 1½ Inches in 10 Feet or More.

Standard Pipe With the Same Size Valve	Maximum B. T. U. Per Minute	Standard Pipe With One Size Larger Valve	Maximum B. T. U. Per Minute	Gain By Larger Valve
¾"	136	¾"	164	20.6%
1 "	330	1 "	389	17.9%
1¼"	575	1¼"	730	27.0% *
1½"	836	1½"	1000	19.6%
2 "	1485	2" pipe	1519	2.3%
"		no valve		

*This apparent excessive increase is due to the fact that a 1¼ inch pipe is 10 per cent larger in diameter than the nominal size.

The above table shows that a substantial increase in capacity is obtained by using a valve one size larger than the nominal pipe size.

As to slope—It is apparent that with certain types of building construction very flat slopes for horizontal runouts are hard to avoid. Since the critical velocity drops very rapidly with a slope less than one inch in 10 feet, flatter slopes should be avoided if possible. A lower limit might reasonably be placed at one-half inch in 10 feet. No advantage seems to be gained by using slopes greater than 1½ inches in 10 feet.

Comparison of Effect of Slope on Capacity of 1¼ Inch Pipe

Slope in 10 Feet	Maximum B. T U. Per Min.
½ inch	448
1½ inch	575
6 inch	566
12 inch	584
Vertical	528

In comparing the effects of slope on the capacity of a runout, it is here shown that an increase in slope from ½ inch to 1½

inches in 10 feet gives an increase in capacity of 28.3 per cent. From this point on, no apparent gain is shown by increasing the slope. This is shown to be true, independent of pipe size.

Since the value of any research problem is ultimately determined by its practical application, it is hoped that the above statements together with the accompanying curves will prove to be of some value to persons dealing with any problems where counter-flowing condensate must be expected.

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 6 December, 1923 Number 7

The Use of Power Fans for Night Cooling of Common Storage Houses

By

H. J. DANA

Specialist in Experimental Engineering

ENGINEERING BULLETIN No. 14

Engineering Experiment Station

H. V. Carpenter, Director

1924

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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INTRODUCTION

Increased production of apples and consequent keener competition for good markets has served to put the grower in need of improved storage facilities for his crop. The ideal storage is conceded to be a first class warehouse equipped with a refrigerating plant. This is too expensive for the average small grower to own and operate. On the other hand, the increased profit due to holding his crop in some central cold storage plant, is frequently more than offset by the storage rental he must pay.

Consequently, the need has arisen for a cheap and simple means by which the individual grower can store his crop in his own warehouse and preserve it until such time as he can ship at a profit. It is especially important to precool the summer and early fall varieties such as Jonathan, Delicious, etc., as soon as picked. Many growers and fruit men are realizing the importance of early and rapid cooling in keeping up the quality of their product until it can be marketed.

At the earnest solicitation of apple growers who are also members of the Washington State Horticultural Association, members of the Staff of the Engineering Experiment Station, in cooperation with the Department of Horticulture of the State College of Washington, set about to collect information on the subject of cooling common storage houses. Refrigerating plants have already been carefully studied and are known to be the most effective means of cooling fruit, but their high first cost makes them prohibitive to the small grower. Therefore, they cannot be considered in this work.

The most promising method next available was the use of power fans for delivering cool air to the house at night. There seemed to have been very little information available on the successful application of fans to this work. In fact, several such installations were reported unsuccessful as far as cooling was concerned.

For this reason, experiments were made in which a fan was installed and temperature observations made of the possible temperature reductions which could be accomplished. Through the courtesy

of Col. Paul H. Weyrauch, then President of the Washington State Horticultural Association, a temporary installation was made and tests run in the Blalock Fruit and Produce Company's warehouse at Walla Walla. In co-operation with Professor O. M. Morris, of the Department of Horticulture of the State College, a fan was installed in part of the apple storage on the State College Campus, and records made of the temperatures prevailing with and without the use of a fan. The suggestions and services of Professor Morris were invaluable in carrying out this work.

Since these investigations were begun we have learned of two or three growers and companies who have installed fans in the manner suggested, and we have endeavored to secure and incorporate such data from them as would be of use to the apple growers of the State.

Therefore, we believe the work along this line is justified because it seems of very great value to the grower, and thus far, has not been collected and organized for his use.

THE USE OF POWER FANS FOR NIGHT COOLING OF COMMON STORAGE HOUSES

If the apple crop of the United States could be marketed at a good price within a few days after it was picked in the fall, then the growers would need packing houses only, and a report of investigations of methods of cooling common storage would be unnecessary. However, past experience has demonstrated that there is sometimes an advantage to the small grower in being able to hold his apples in storage for better markets, which usually occur during the late winter or early spring. The two main objections to deferred marketing arise: first, from the expense of storing in central refrigerated warehouses; and second, from the large losses sustained by the grower who attempts to hold his crop in his own common storage house.

In the handling of those early fall apples which are not to be stored it is not uncommon for marketing to be delayed several weeks or even a month or more after picking. If the apples are allowed to retain their heat during this normal and necessary lapse of time, the ripening proceeds so rapidly that heavy losses are certain to follow. Also, the further the ripening process progresses, the less effective is any amount of cooling.

*We wish to express our appreciation of the generous suggestions and assistance given us in the preparation of this work by Mr. J. L. Dumas and Mr. Loren F. Dumas of Dayton, Washington; the Peshastin Fruit and Produce Co., of Peshastin, Washington; and Mr. C. L. Robinson, Secretary of the Washington Horticultural Association, of Olympia, Washington. We wish especially to mention the fine assistance and co-operation of Col. Paul H. Weyrauch, President of the Blalock Fruit and Produce Company, of Walla Walla, in furnishing equipment and in conducting cooling tests at his warehouse.

We wish also to thank Professor O. M Morris of the Department of Horticulture of the State College for his co-operation in making storage tests, and for his helpful suggestions in the preparation of this manuscript.

Effect of High Temperatures on Rate of Ripening

Horticulturally speaking, an apple continues to ripen after it is picked until the cell structure undergoes a change known as rot, making the fruit totally unfit for use. Even less advanced stages of ripening make the apple less desirable for eating. Therefore, it is highly important to retard this ripening as much as possible immediately after picking and to continue to retard the process until the apple is used. According to investigations of the United States Department of Agriculture, and of others, the keeping quality of the apple at different temperatures is closely related to the amount of respiration taking place; that is, the rate at which carbon dioxide is given off. Assuming the rate of respiration at 32° to be 100%, the rate at 35° is 150%, at 65° the rate is 700 to 800% and at 80°—a common temperature at which early fall apples are picked—the rate is 1600 to 1800%. Since this respiration may be taken as an indication of the rate of ripening, it can be seen how important it is to reduce the temperature of the fruit as soon as possible after it is picked.

An apple kept at 90° will ripen to the point of damage for use in approximately one week. If maintained at 32° and other conditions

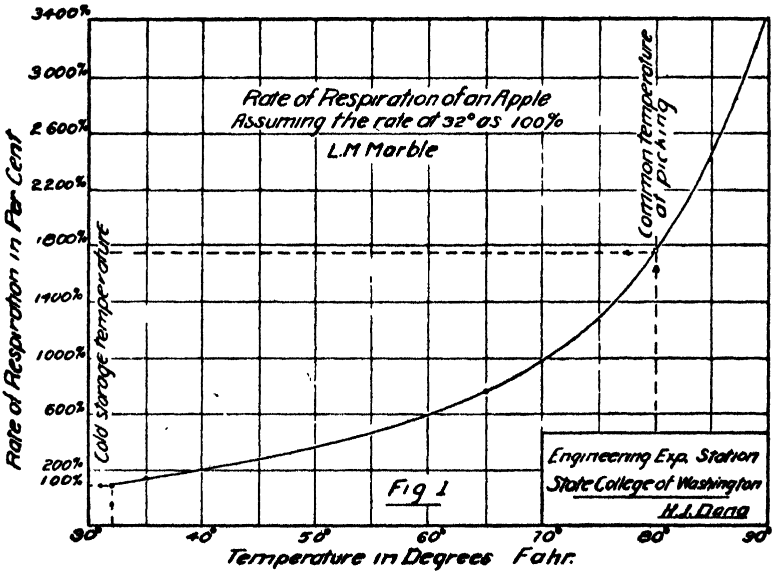
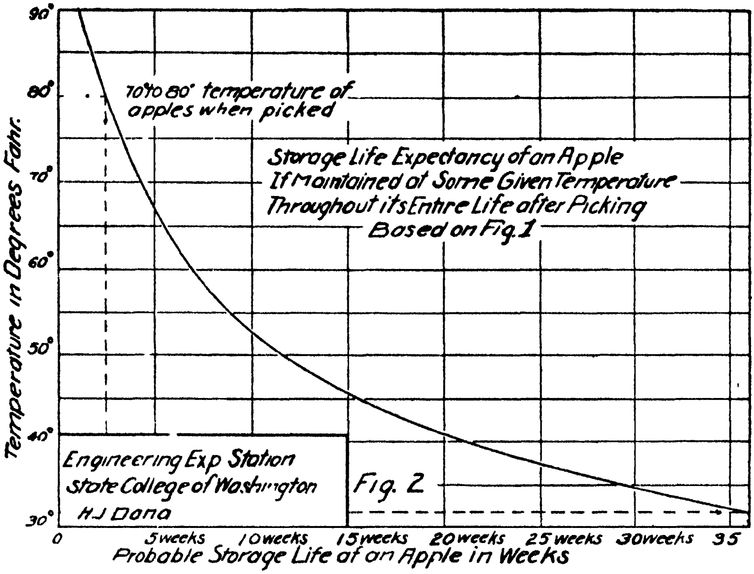


Fig 1

are favorable, the same apple may be successfully stored for from five to nine months. For the purpose of illustration, we will assume the life in 32° storage to be nine months, or 36 weeks. Then using the rate of ripening shown in Fig. 1 as a basis, we can show the life expectancy of an apple at different temperatures approximately as in Fig. 2.



The Necessity for Immediate and Rapid Cooling

From these two illustrations will be seen the importance of quickly cooling an apple immediately after it is picked. It is often possible to secure considerable reduction of temperature by leaving the fruit in the field boxes out in the orchard over night. Then haul them into the storage house early in the morning before the sun warms them up again. This may require additional hauling facilities for part of the day, but a number of growers have added such equipment and find it pays.

As an illustration of the importance of immediate cooling: Fruit is to be stored for five months. It is picked and put into the warehouse at 70°. Due to the prevailing outside temperatures, the fruit will cool but very little in storage for the next thirty days, unless

lowered by some special mechanical means. In a little over a month, this fruit has reached the end of its storage life, and must be placed on the market and consumed at once, or suffer loss. Consequently, it will be useless to place the fruit in cold storage at this late time.

On the other hand, if the same fruit had been cooled immediately to 40° and held at that temperature, the storage life would have extended approximately to the end of the five-month period, at which time it could be placed on the more favorable market prevailing in the early spring.

Refrigerated Storage and Common Air-Cooled Storage

Refrigerated storage is the ideal storage. However, the refrigerating machinery for a warehouse built to care for the crop of a ten- or twenty-acre orchard will cost $3,500 to $7,000 installed, not including insulation for the refrigerated room. This cost, in most cases, is not justified by the increased returns possible to the small grower, since the plant will be in use but a small part of the year.

The alternative, therefore, for the average grower, is to cool his apples as quickly as possible by taking advantage of the reduced air temperatures which occur at night, during the picking season.

Fig. 3 shows the monthly average of the daily maximum and daily minimum temperatures prevailing in the year 1922 in several representative cities in the apple growing districts of Washington. The maximum temperatures occur in the daytime and the minimum at night. It will be noted that during the apple picking season, September 15 to November 1st, the difference between maximum and minimum is at least 25 degrees. Often the daily difference is considerably more than this.

The average temperature of apples when picked in September is probably somewhere around 70 degrees. Many times it is much greater than this. If the apples are stored immediately in a common storage warehouse, the natural circulation of the air will carry away the heat very slowly, because only for a few hours during the night is the air temperature very much lower than 70°.

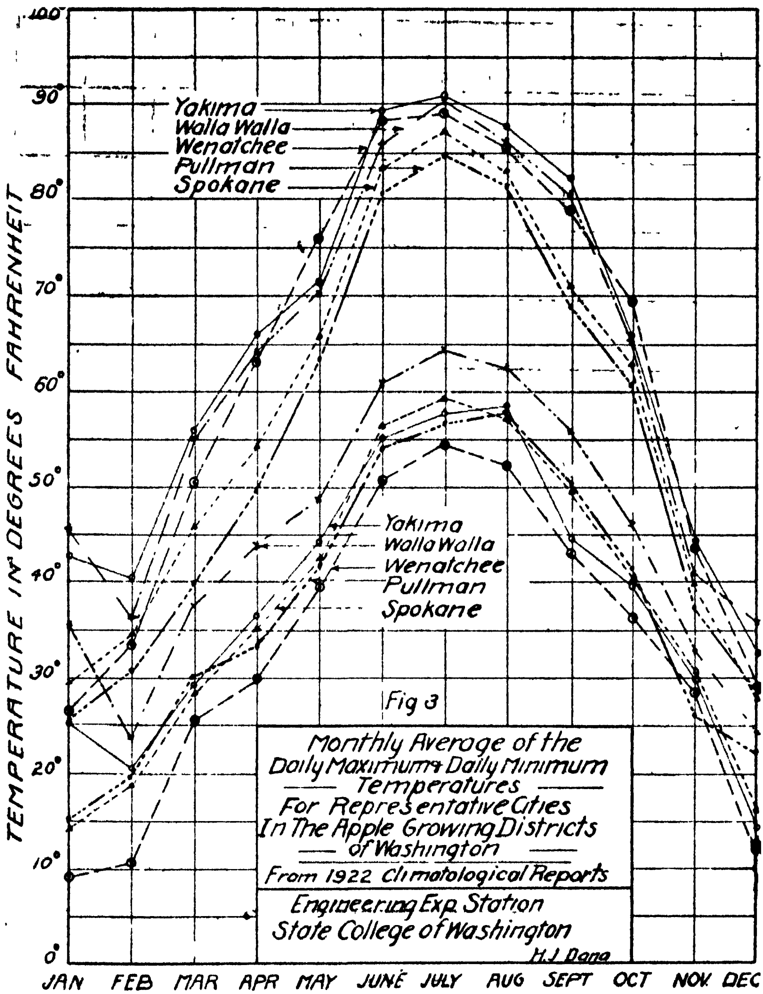
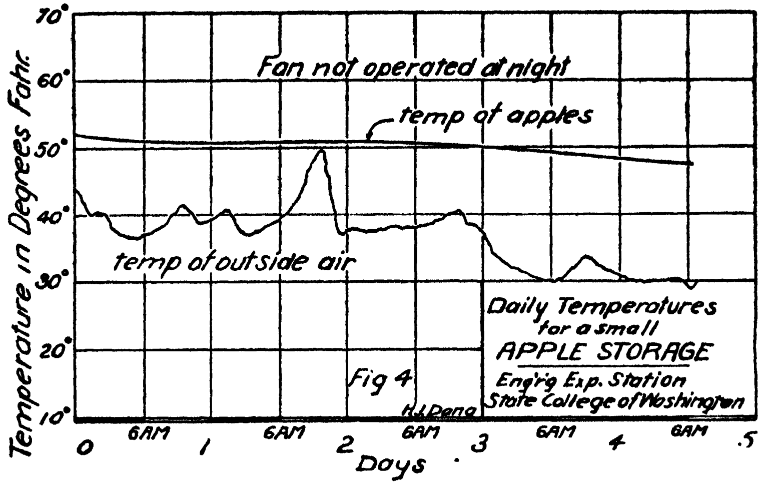
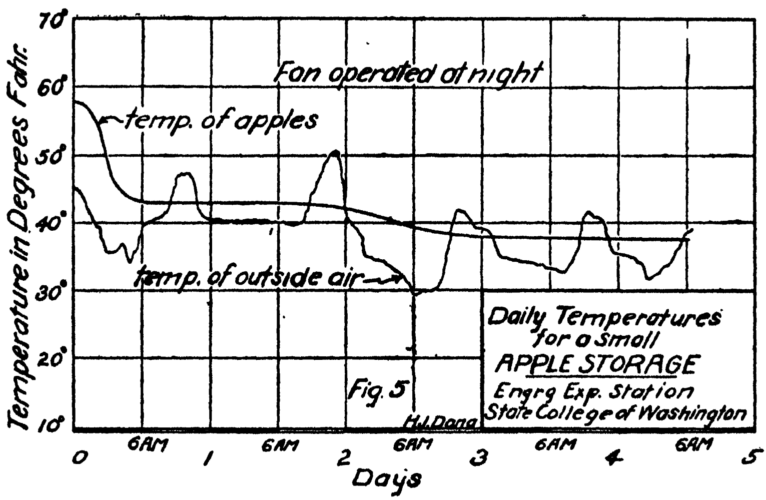


Fig. 4 shows a chart of the outside air temperature and the temperature of the stored apples in a small common storage. The movement of the air depends entirely upon natural circulation, coming in through windows and going out through a restricted roof ventilator. It will be noted that the temperature of the apples remained well above the maximum outside temperature of the air. Obviously, if the lower outside temperature prevailed long enough, the apples



themselves would ultimately reach a lower temperature, but a large lot of apples would cool still more slowly than is shown here for this small lot. In the meantime, however, they would continue to ripen at a very rapid rate.

Fig. 5 represents outside air temperatures and apple temperatures in the same storage house ventilated by a power fan. A small lot of apples at a temperature of 58° was placed on a false floor under



which the air from the fan was being delivered. This air was forced upward through the apples in the boxes and escaped through the roof ventilator. Due to the comparatively large volume of air used on the small lot of apples and the care used to make the air all go through the boxes, the initial cooling was accomplished in a remarkably short time. After the initial cooling, it will be noted that the temperature of the apples holds approximately to an average between the maximum and minimum outside air temperature. Comparing Fig. 5 roughly with Fig. 4, it will be seen that with approximately the same average air temperature, with the aid of the fan, the temperature of the apples is maintained some ten degrees lower.

This temperature reduction, we have found, in other tests can ultimately be carried down to within 4 or 5 degrees of the minimum temperature of the air being used.

Correct Installation of Fan is Necessary for Success

A number of attempts have been made to use a fan for ventilating storage houses, where the air was discharged into the room at one end of the building and allowed to vent at the other end of the room. This cools the air in the room and those apples on top of the stack. However, the temperature of the apples in the boxes inside the stack are affected very little. Consequently the use of the fan in this manner has not improved the condition of any but a few of the outside apples, and therefore has been pronounced a failure.

It is important that the air be brought into intimate contact with the apples, and the best method yet developed to do this is to apply the air under a false floor and force it up through the boxes stacked thereon. The most succesful plan is to install a power driven fan of ample capacity to deliver cold night air under the false floor of the common storage house. The apple boxes are stacked closely to cover the entire floor. If only part of the floor is used for storage some provision must be made to restrict the air to this part, otherwise most of the air will escape through the floor cracks not covered and not be forced through the apples at all. For this purpose the space between the false floor and the sub-floor may well be divided into several sections by partitions, and the discharge duct arranged to

deliver air only into those sections which are covered with boxes. If the air is free to discharge either through the boxes or through uncovered cracks in the floor, the major part, of course, will follow the easiest path of escape through the uncovered floor, doing no good whatever. The discharge of the air after passing through the apples may take place through the vents in the roof, and also through doors, windows, etc.

Large Quantities of Air Necessary for Cooling

The amount of air required to accomplish a reduction of temperature of one degree for a quantity of apples is very large. For instance, to cool one pound of water one degree we must take from the water a unit of heat known as one British Thermal Unit. In order to accomplish the same amount of cooling with air, we must reduce 55 cu. ft. of air one degree F. The pound of water can be contained in a box measuring approximately 3 inches on a side, while 55 cu. ft. of air at atmospheric pressure will fill a box measuring 3¾ ft. on a side. This is to emphasize the idea that a very large volume of air is necessary to reduce the temperature of a box of apples from 70° to 40°. The heat capacity of a pound of apples is less than that of a pound of water, being approximately .95 where the heat capacity of water is 1.00. Therefore, in cooling a pound of apples 30° or from, say 70° to 40°, the number of British Thermal Units of heat which must be carried away by the air would be 30 x .95=28.50. To carry away this amount of heat would require 28.50 x 55=1567.5 cu. ft. of air to be changed one degree in temperature, or 783.7 cu. ft. changed two degrees, etc.

If a box of apples weighs approximately 40 pounds, then 10,000 boxes would weigh 400,000 pounds; and to cool this amount of apples 30 degees would require 627,000,000 cu. ft. of air if the air be raised only one degree in temperature. We will assume, for example, that the air in passing through the apples, is raised an average of 4°. The amount of air required then will be ¼ of 627,000,000 or 156,750,000 cu. ft. If a fan is installed which delivers 20,000 cu. ft. of air per minute, and the outside air temperatures are such that cooling can be accomplished only during 10 hours of each night, the amount of air handled per night will be 12,000,000 cu. ft. Then

the time required to handle the total amount of air necessary to cool the above lot of apples will be 156,750,000÷12,000,000=13 nights.

During this time there will undoubtedly be a slight warming up each day due to the higher temperature prevailing in the middle of the daytime, but this is very small when the quantity of fruit is large. Also the night time temperatures will not be uniformly low—some nights perhaps being too warm for the fan to be operated at all, and other nights being even cooler than the average. Therefore, it is evident that the number of nights necessary to accomplish the required cooling might easily exceed the above stated number.

It will also be true that when very warm apples are brought in from the orchard and stored immediately in a fan cooled house, the air forced through them the first night will be raised several degrees in temperature, so that a comparatively small amount of air will effect a great amount of cooling. This is fortunate and desirable as shown in Fig. 1 and Fig. 2, since it is highly important to secure a large and rapid initial cooling to check the ripening process as soon and as much as possible. This rapid cooling when the apples are warm is shown in Fig. 5.

Small Window Fans Not Effective

The above figures will show the futility of attempting to accomplish any material cooling of a storage house full of boxed apples by the use of a propeller or similar type of fan in a window or opening at one end of the building. Great quantities of air must be blown **through** the boxes and this can best be accomplished by delivering the air under a false floor and forcing it up through the closely stacked boxes. After it has passed through the boxes it is immaterial whether it escapes from the building through the doors and windows or through a roof ventilator.

Roof Fans Not Entirely Satisfactory

The objection to placing a suction fan in the roof ventilator and depending upon this to move the air is that great care must be used in keeping doors and windows closed and cracks and leaks well sealed. The air entering a door or window will not pass through the boxes, but over them and out through the roof fan, doing no

good in cooling any but the very outside of the stack. With the air discharged under the apples it can be so handled that the only escape is up through them, and in passing through, the work of cooling is done, making the method of final escape of the air immaterial.

A power fan installation such as we have suggested above is in present use at Peshastin, Washington. A room 190x80x10, holding about 50,000 boxes, uses an 8 horsepower fan, delivering 20,000 cu. ft. of air per minute. This gives about 8 air changes per hour when the room is empty of fruit. However, when filled with boxed fruit, the air space remaining would be only approximately ¼ the volume of the entire room. This would give one air change about every two minutes. Although no accurate record was kept of the temperatures obtained, the management of the Peshastin plant reports that the use of the fan was highly satisfactory.

On a small scale test made at the State College on 27 boxes closely stacked three deep on a slatted floor, a fan was used which delivered 240 cu. ft. of air per minute. In eleven hours of operation, this fan reduced the temperature of 1080 lbs. of apples from 58 to 42°, or 16°, removing 16,420 BTU. The amount of air delivered in eleven hours was 158,000 cu. ft. On an average therefore, each BTU of heat was carried away by 9.7 cu. ft. of air, which in passing through the apples, was raised in temperature 5.7°. The air temperature during this time ranged from 45° down to 35° F.

Air May Be Humidified

Where the fruit shows a tendency to wilt due to very low humidity, the moisture content of the air can be increased by directing a continuous fine spray into the draft from the fan. Or, where desirable, the floor under the false floor may be covered with water which will be evaporated by the air passing over it. Another method of adding moisture to the air is to direct the air from the fan over baffles of burlap kept wet continuously. The evaporation of the water in the air draft has the additional advantage of lowering the air temperature before it strikes the apples.

Ample Size Fans Most Efficient and Effective

It is easily recognized that the slower the movement of air through the boxes, the more nearly will its temperature be raised to

the temperature of the apples, but it will not carry away a large amount of heat because only a small quantity of air is used. If the air passes through with greater velocity, it will take up nearly the same amount of heat per cu. ft. and the larger volume will accomplish a larger amount of cooling. The rapid air movement will accomplish rapid cooling but will require a larger and more expensive fan and motor. Rapid cooling is valuable since it makes it possible to take fuller advantage of a night that is cooler than the average. The proper solution therefore, is to use a size of fan which will accomplish a reasonably rapid cooling and still not be too high in first cost or in operation. The grower must judge of the value of rapid cooling of his crop and then choose a fan accordingly.

Any type of fan of sufficient capacity may be used for cooling common storage. However, there is a great deal of difference in the amount of power needed to drive different kinds of fans of the same capacity. It is cheaper in the end to pay a little more at first for an efficient fan and then use a smaller motor and operate at a lower power consumption, than to buy a cheaper fan and pay larger power bills. The most efficient kind of a fan for this work is the multivane type in which the runner is equipped with a large number of carefully shaped blades. The cheaper and less efficient type of fan has four or six large blades and is known as the plate type.

Since operating cost is more important than first cost, reference to Table 1 will show the desirability of buying a large fan. The larger the fan within proper limits and the slower the speed, the smaller will be the motor required to deliver a given quantity of air. The underscored data show the amount of air delivered by different sized fans using approximately 2 H.P. The table shown is based on one half inch water pressure, however, the actual working pressure of any installation will depend upon the volume of air delivered, the size of the ducts leading under the false floor, the area of the floor, and the number of boxes and method of stacking same, and the area of the exhaust vents. The following is an illustration of the use of the table.

Example: What power will be required to deliver approximately 13,000 Cubic Feet of air per Minute at one half inch water pressure, or .289 oz. gage pressure per sq. in.?

Table I. Horse Power required to deliver various volumes of air at one half inch water pressure, using a multi-vane type fan of modern make and design.

Tip Speed	Size No. 2			Size No 4			Size No. 6			Size No. 8			Size No. 10		
FPM	RPM	CFM	HP	RPM	CFM	HP	RPM	CFM	HP	RPM	CFM	HP	RPM	CFM	HP
2200	646	991	.140	431	2230	.315	324	3970	.56	216	8920	1.25	162	15900	2.25
2400	705	1300	.220	470	2920	.495	353	5200	.88	235	11700	2.00	176	20800	3.5
2600	765	1520	.305	510	3450	.69	382	6140	1.25	255	13800	2.75	191	24600	4.9
2800	824	1740	.405	549	3920	.92	412	6970	1.65	275	15700	3.65	206	27900	6.5
3000	882	1930	.520	588	4340	1.15	441	7720	2.05	294	17400	4.6	221	30900	8.2
3200	941	2110	.650	627	4750	1.45	470	8450	2 60	314	19000	5.8	235	33800	10.5
3400	1000	2280	.780	667	5130	1.75	500	9120	3.10	333	20500	7 0	250	36500	12.5
3600	1059	2450	.940	705	5510	2.10	529	9800	3.75	353	22000	8.5	265	39200	15.0
3800	1118	2610	1.10	745	5860	2.50	559	10400	4 4	373	23500	9.9	280	41700	17.5
4000	1177	2770	1.30	785	6230	2.90	588	11100	5 2	392	25000	11.5	294	44300	21.0
4200	1236	2920	1.50	824	6560	3 40	618	11700	6.0	412	26300	13.5	309	46700	24.0
4400	1294	3090	1.75	862	6950	3.95	647	12400	7.0	431	27800	16.0	324	49500	28.0
4600	1353	3240	2.00	901	7280	4.50	676	13000	8.0	451	29200	18.0	338	51900	32.0
4800	1412	3400	2.30	941	7650	5.10	706	13600	9.1	471	30600	20.5	353	54400	37.0
5000	1471	3550	2.60	980	8000	5.80	735	14200	10.5	490	32000	23.5	368	56900	42.0

FPM=ft. per minute tip speed of fan blades.
CFM=cubic ft. of air per minute which the fan will deliver under these conditions.
HP=horsepower required to drive the fan.
RPM=revolutions per minute.

Solution: From table 1, a No. 6 fan will require 8 H.P. to deliver 13,000 C.F.M.; a No. 8 fan will require 2.75 H.P. to deliver 13,800 C.F.M.; and a No. 10 fan will require 2.25 H.P. to deliver 15,900 C.F.M.

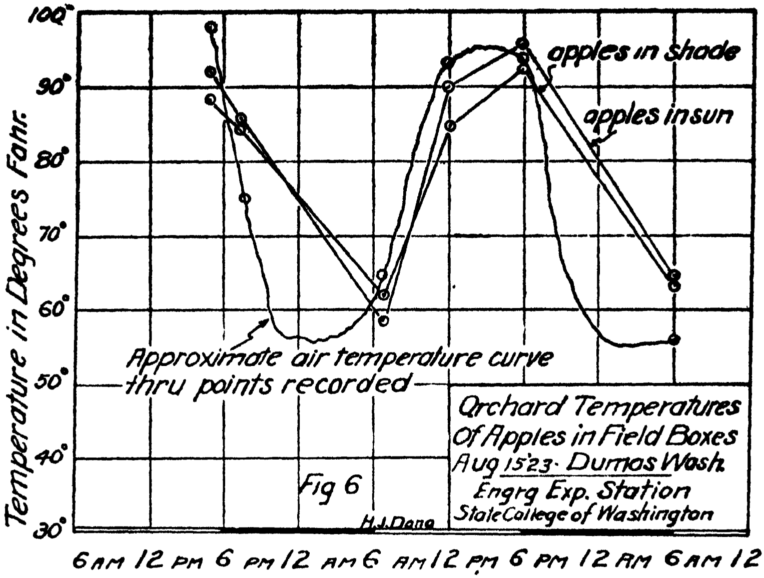
In considering the purchase of a fan for cooling a storage house, full data on size of house, quantity of apples handled, kind of power available, and other local conditions, should first be determined. If the building is already equipped with a false floor, the application of forced ventilation will be simple. The building itself should be as well insulated as for common storage. As stated above, the fan selected should be of ample capacity. The Engineering Experiment Station of the State College will be glad to offer recommendations as to size, type and kind of fan installation suitable for those who wish to convert their present warehouse or common storage.

Without specific information, the cost of a fan installation for any particular warehouse can only be approximated. If the house is built according to the plan of the common storage house recommended by the U. S. Department of Agriculture, no alteration of the building will be necessary. A fan installed just outside the building may discharge under the false floor. If located inside the building, the supply may be taken in through a window or special opening, and discharged under the floor. Or, the fan may be installed in another building and the air conveyed to the storage building through a proper sized duct. This is not recommended ordinarily because of the losses by friction in the pipe.

Ample Air Vents are Important

Ample provision should be made for the air to escape from the building after it has passed through the boxed apples. This may be through one or more roof ventilators or through a number of doors and windows. If 20,000 cu. ft. of air is delivered to a room every minute and forced to escape from that room through a roof ventilator 2 ft. square, the velocity of the air through the ventilator would be 5,000 ft, per minute or almost 60 miles per hour. It is a needless waste of power to require such a high velocity of the discharged air. Furthermore, this waste of power will materially reduce the volume capacity of the fan, and therefore lower its cooling efficiency. The

total area of all air ducts, ventilators and air exits should be several times the area of the discharge opening of the fan itself.



Orchard Cooling Very Effective

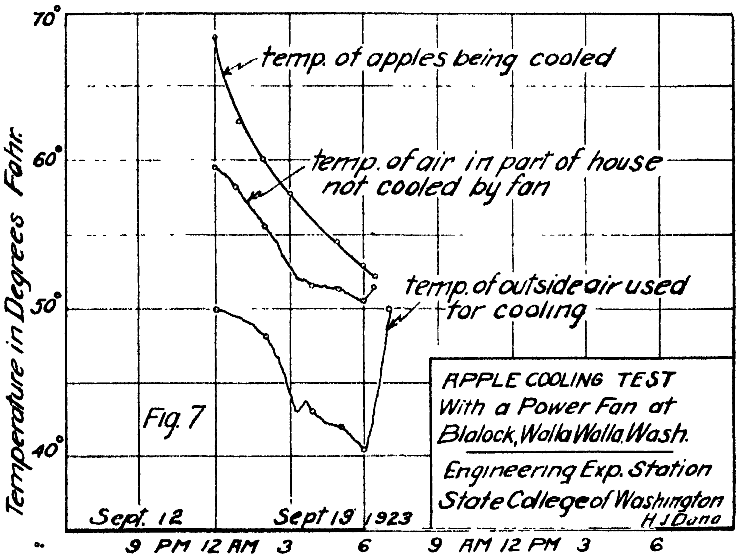
Fig. 6 shows the reduction of temperature it is possible to secure by leaving apples in the orchard over night and hauling to the warehouse in the early morning. If hauled during the time between 4 and 8:00 a.m. the temperature will be from 25 to 35° lower than if hauled during the afternoon. Such a method of handling will require an expenditure for additional help with perhaps a slight increase in wages. However, the cost of thus lowering the temperature of the apples approximately 20 degrees in one night will amount to only a fraction of a cent per box, as against the fact a fan installation will require several nights to accomplish the same cooling at a slightly greater cost.

Apples picked and orchard cooled in early October and stored can be still further cooled by a fan installation, particularly since the nights get cooler very rapidly as shown in Fig. 3.

Orchard cooling is of primary importance and should be practiced by every grower whether he owns and manages his own warehouse,

or hauls direct to a central co-operative house, and even though means for further cooling are used.

Fig. 7 shows the results of a test made in cooling apples with a fan after being brought into the warehouse. Since the house was open all day, and not insulated for common storage, the reduced temperature could not be retained after it was once secured. Consequently, but one night's performance is shown.



Paper Wrappers Hinder Cooling

It is very important to cool the apples as much as possible before they are wrapped in paper and packed. Paper is a fairly good heat insulator, and furthermore, its presence around the apple prevents free circulation of the air in and through the boxes. Consequently, paper wrapped and packed apples will be much more difficult to cool either in common storage or by forced ventilation, than loose apples in market boxes.

Fig. 8 illustrates the general scheme of a warehouse equipped for forced ventilation. The house should be insulated. This may be done cheaply by filling between the inner and outer board walls

with kiln dried planner-shavings, well tamped in place. Both the inner and outer walls should include a layer of tar paper to prevent the entrance of moisture into the insulation.

Note should be taken of the plan to restrict the air under the false floor to the section covered with boxes. This is important as air leaks greatly reduce the effectiveness of the fan.

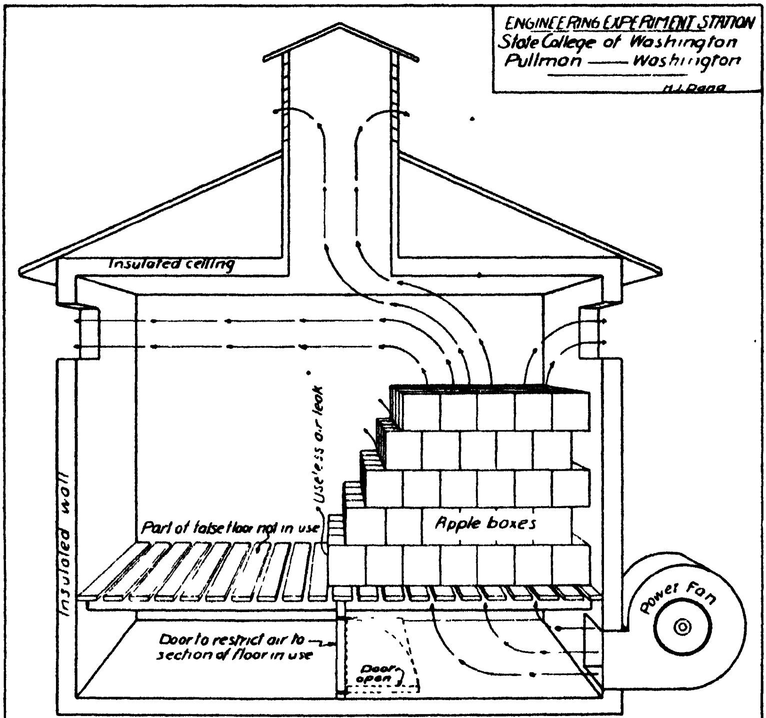


Fig. 8 Section of fan-cooled common storage house showing point of delivery, and method of discharge, of the air

RECAPITULATION

Warm apples ripen very rapidly; over-ripe apples are not good sellers, therefore they are not profitable.

It is important to cool apples as rapidly as possible after picking, first by orchard cooling over night, and then by warehouse cooling, with forced ventilation at night.

Large lots of apples in common storage are "protected" against proper cooling just as they are against freezing by the thick walls and lack of sufficient ventilation.

Cold storage is the ideal, but is limited to comparatively few because of the large first cost.

The small grower can improve his common storage by the use of cold night air with an equipment costing less than 1/10 the cost of a refrigerating plant—and thus prolong the storage life of his fruit for better markets.

Actual tests prove the practical results obtainable with fan cooling in maintaining low storage temperatures.

Multivane type of fan is most efficient to use, and may be located inside or outside the building. It will be cheapest in the end to use a fan of ample dimensions, requiring smaller motor and smaller power cost to operate.

The benefits from using forced ventilation in cooling apple storage should apply equally well to the cooling of other kinds of fruit and vegetables.

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 7 Sept 1924 Number 4

A Universal Laboratory Standard Meter for AC-DC

By H. V. CARPENTER,
and H J DANA

ENGINEERING BULLETIN No. 15

ENGINEERING EXPERIMENT STATION
H. V. CARPENTER, Director

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug 24, 1912

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STANDARD LABORATORY TRANSFER INSTRUMENT

Introduction and purpose

Need for Universal A. C. D. C. transfer instrument

Qualifications to be met

Type of Instrument

Error due to deflection

Error due to inductances of windings

Voltmeter

Wattmeter

Analysis of Suspensions

Mathematical analysis of single suspension

Mathematical analysis of bifilar suspension

Comparison of restoring force

Sensitivity of Instrument

Optical system and scale

Smallest reading in per cent of full scale

Stability of zero

Description of Construction

Circuit

Optical system

Construction as a voltmeter

Construction as an ammeter

Citations

Analytical Mechanics, by E. H. Barton.

Handbuch der Physik, by Winkelman. Article by Auerbach.

Philosophical Transactions 1914—

Article by A. N. Shaw. P147.

Dictionary of Applied Physics, by Glazebrook, P 139 etc.

Electrical Measurements, by F .A. Laws, P 313—

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Requests for copies of the engineering bulletins and inquiries for information on engineering and industrial problems should be addressed to The Engineering Experiment Station, State College of Washington, Pullman, Washington.

The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

UNIVERSAL
LABORATORY STANDARD METER

Introduction

The instrument herein described was designed and built with the following purposes in view:

1. To serve as a laboratory standard for use in calibrating portable instruments, more particularly of the alternating current class which cannot be checked directly with the ordinary direct current potentiometer.

2. To develop a type of instrument in which full advantage is taken of the conditions resulting from abandoning portability and mounting the instrument permanently on a solid support.

Comparing the proposed type of standard instrument with the semi-portable types now available, it appears that the stationary type must depend for its calibration on a check against a semi-portable standard, or be so designed as to permit calibration with direct current and potentiometer. The semi-portable type on the other hand, may be calibrated in some other laboratory but if so, it must hold its adjustment unchanged while being transported.

It has been found in this study that the stationary type of instrument can be so designed as to have the following points in its favor to offset the loss of portability:

1. Freedom from pivots, pivot friction ,and pivot shift.

2. Freedom from springs and variations in elasticity.

3. Less needed torque on the moving element to insure accuracy, permitting less current and therefore more resistance in the circuit of the moving element.

4. Removal of limitations on the pointer and scale that can be used, through the possibility of using a suitable optical system.

5. Simplified construction and therefore lessened cost.

6. Removal of weight limitations in construction.

7. May be made astatic without serious disadvantage.

The instrument here described as necessarily fixed in position can easily be shipped ready for installation but is not intended to be easily moved about in the laboratory. It will usually be calibrated with a direct current potentiometer after installation though there is no reason why it should not hold its calibration closely while being shipped.

Magnetic Balancing

The moving element consists of two coils connected in series and placed in the same vertical plane, one above the other with their magnetic axes 180° apart. With this arrangement, any positive rotating torque of one coil due to the earth's field or any stray field will be balanced by an equal negative torque of the other coil. When first erected and tried out, it was found that current in the moving element, actually did cause rotation ' This was found to result from one coil embracing more magnetic area than the other, and was remedied by compressing, or narrowing one coil slightly until magnetic balance was secured.

Optical System

To the moving element was attached a small high quality front surface plane mirror. The scale was placed above and practically in the plane of the front of the instrument and with a radius of curvature equal to 1.6 times the distance to the suspended mirror. This curvature gives a straight line relation between deflecting force and scale readings. Just in front of this mirror, another front surface mirror was located at an angle of 45° for the purpose of deflecting the light from the scale into the first mirror. The scale was located 196.5 centimeters above the center of the suspended mirror, and was illumined by shielded lights. The angle mirror is 7 centimeters from the suspended mirror. A high grade galvanometer telescope was set up to receive the scale reflection from the suspended mirror. With this system, the effective length of the optical pointer arm of the instrument is $2(196.5+7) = 407$ centimeters, while the total distance from the telescope to scale is only

about 213 centimeters. The length of the scale is 50 centimeters. The angle of rotation of the moving element for full scale deflection is represented by the angle measured by an arc of 50 centimeters at a radius of 407 centimeters. This gives full scale deflection with an angular deflection of only:

$$\theta = \frac{L}{.01745r} = 7.04^\circ$$

The scale is divided into millimeter divisions and deflections can be estimated to tenths of millimeters, thus making it possible to read accurately to one part in 5000, or to two one-hundredths of one per cent of full scale.

Suspension System

The single wire suspension is the simplest and most common type in use for galvanometers. The restoring couple is a direct function of the characteristics of the suspending wire, as follows:

$$F = \frac{\theta E}{L} \frac{\pi r^4}{2}$$

Where

F = The restoring moment of a single wire.

θ = The angle of deflection in radians.

L = The length of the suspension wire.

$\frac{\pi r^4}{2}$ = The polar moment of inertia.

r = Radius of the wire.

E = Modulus of elasticity of the wire.

Since F and θ are the only variables in the equation for a given suspension, this equation may also be written as follows:

$$F = K\theta$$

In this type of suspension, the weight of the coil does not enter into the restoring moment.

The single wire type of suspension, usually employing a flattened wire, is almost universal for galvanometer work where very

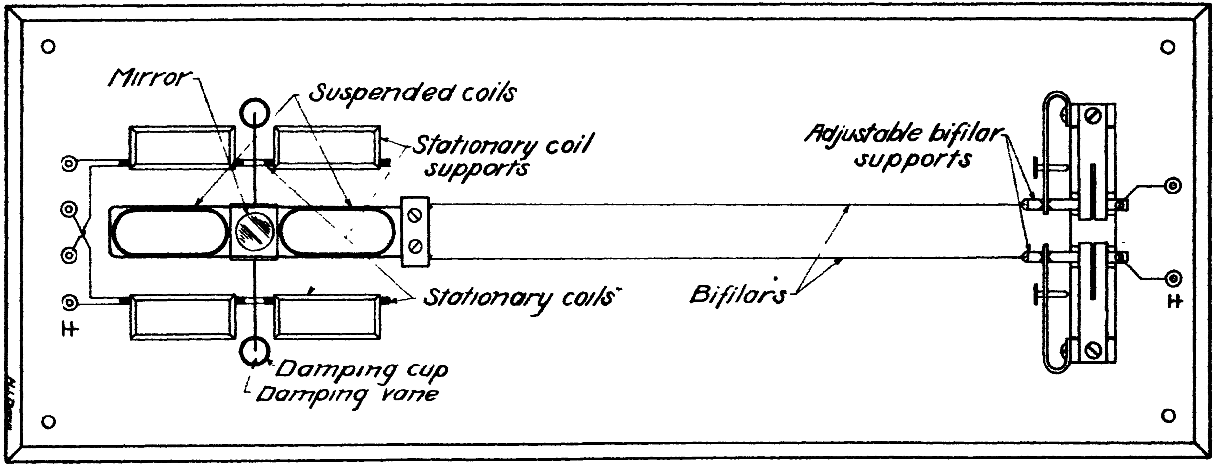

Fig. 1 shows the diagram of the circuits and the connections employed in the meter described.

weak restoring forces are important and great stability of zero reading, and constancy of sensitiveness are not expected. For an instrument such as is here proposed, high sensitiveness as compared with a galvanometer is not needed, but constancy of zero and restoring force are vital. This suggests the bifilar type of suspension.

The bifilar suspension system makes use of two similar wires or strips supported a given distance apart at the top and attached at separate points on the suspended coil. In this case, the restoring moment will be the sum of two separate moments. First, there will be the torsional moment of the suspension wires themselves, which since there are two wires, will be:

$$F_t = 2K\theta$$

Second, there will be a restoring moment characteristic of the bifilar method of suspension which will be:

$$F_b = \frac{Wg\,\frac{a^2}{4}\sin\theta}{\sqrt{L^2-4\,\frac{a^2}{4}\sin^2\frac{\theta}{2}}}$$

Where:

F_t is the torsional restoring moment of the two wires.

F_b is the restoring moment due to the bifilars.

a is the distance between the bifilars.

L is the length of the bifilar wires.

W is the mass, or the weight of the coil.

θ is the angle of deflection in radians

If the angle θ of deflection is small, the formula reduces to the following form:

$$F_b = \frac{Wga^2\sin\theta}{4\,L}$$

The total restoring force will then be the sum of the two separate forces, or:

$$F = F_t + F_b$$

$$= 2\,K\theta + \frac{Wga^2\sin\theta}{4\,L}$$

The following example will show the comparative value of the two restoring forces. The values given are approximately correct for this instrument.

θ = .1222 radians, or 7 deg., max. deflection
L = 40 cm.
W = 20 gm.
a = 1 cm.

FOR SINGLE WIRE SUSPENSION

The final suspension material adopted was phosphor bronze strip rolled from .0025 wire.
F_t was found by experiment to be .0305 dyne-cm. per radian for one strip, or .061 dyne-cm. for the two used.

FOR BIFILAR SUSPENSION

$$F_b = \frac{Wga^2 \sin\theta}{4\ L}$$

$$= \frac{20 \times 981 \times 1 \times .1219}{4 \times 40}$$

$$= 14.9 \text{ dyne-cm.}$$

Then the combined restoring force exerted in the bifilar suspension will be:

$$F_{total} = 2F + F_b$$
$$= 14.961 \text{ dyne-cm. at full scale deflection.}$$

It will be seen that the bifilar restoring force is 244 times that due to the two strips. This assures the positive return to zero which is necessary in an accurate direct reading instrument.

Phase angle error as a wattmeter

Since the deflecting force on a wattmeter pressure coil is actually proportional to I_{st} of the stationary coil times I_{sus} of the suspended coil times the cosine of the phase angle between these two currents, we assume it to represent the power supplied to the circuit, or $I_{st}E \cos\theta$. This means that if I_{sus} lags behind E by any appreciable angle, an error will appear in the readings. This error

is greatest in low power factors where a slight error in θ causes an almost equally large error in $\cos\theta$. Such an error is inherent in all wattmeters of this type and is due to the necessary inductance found in the suspended coil of the instrument. It is usually neglected in ordinary wattmeter readings, first; because the power factor is usually high, giving a small error, second; because the voltage is usually 110 or more, permitting a large non-inductive resistance in the pressure coil circuit, thus reducing the effect of the coil inductance. When used for readings of low power factor, or for low voltages or both, the error must be eliminated for work of any great accuracy. Examination of the relations involved shows that the error just discussed becomes greater for higher frequencies. Since the magnitude of the error depends upon the power factor of the load being measured, upon the frequency, and upon the voltage tap selected on the instrument, correction is not only tedious but it is hard to be sure when correction is necessary.

In view of the above considerations it becomes quite desirable that a laboratory standard wattmeter should be so compensated as to practically eliminate this error for all conditions. This can be accomplished if the current through the suspended coil can be brought into phase with the applied voltage for all voltages and frequencies. To neutralize inductance requires capacity and to get the needed increasing compensation with increasing frequency requires that capacity be used in parallel with resistance or impedance. Capacity in parallel with the coil of the wattmeter might bring the total current of the pressure coil circuit into phase with E but the coil itself would be still further out of phase with E, so that the remedy lies in shunting all or part of the series resistance of the pressure coil circuit with a condenser. The parallel circuit thus made will take one current I_r in phase with the voltage E' across it while the condenser branch will take a current I_c 90° ahead of E'. Thus we have for this parallel circuit a total current leading E' by any angle we choose depending upon R and C. If $w = 2\pi f$, the admittance of this parallel circuit will be as follows:

$$g + Jb = \frac{1}{R} + JwC$$

$$Z = \frac{1}{\frac{1}{R} + JwC} = \frac{R}{1 + JwCR}$$

$$= R - JwCR^2 - w^2C^2R^3 + Jw^3C^3R^4 + w^4C^4R^5 - Jw^5C^5R^6 \ldots\ldots \text{etc.}$$

For a sufficiently small value of wC, terms beyond the second are negligible. For example, test showed the error of the wattmeter to be eliminated at 60 cycles and .12 power factor when a .2 mf condenser was shunted across 54 ohms of the total series resistance. For these values, the parallel part of the circuit gives a calculated impedance of

$$Z = R - JwCR^2 - w^2C^2R^3 + Jw^3C^3R^4 + \ldots\ldots \text{etc.}$$
$$= 54 - J.22 - .0008 + \ldots\ldots \text{etc.}$$

Where the third and later terms of this series can be neglected, the total impedance of the pressure coil circuit can be written:

$$Z = R_s + JwL + R - JwCR^2$$

where $R_s + JwL$ is the impedance of the moving coil of the wattmeter. Thus, if $wCR^2 = wL$, the current will be in phase as required and hold there for all frequencies except such as make the third and later terms of the series given above become appreciable. Trial showed that the value of R could be set very accurately experimentally. The values calculated above indicate a value of .22 ohms for wL which checks with calculation.

For the most exact compensation possible for all temperatures and frequencies, a good mica condenser should be used in which the variation of capacity will not exceed .3% for a variation of frequency from 10 to 1200 cycles, and will not exceed .03% per degree C. The advantage of careful compensation is that after once being made, the instrument can be used freely for a wide range of low voltage, high frequency, and low power factor work where the wattmeter has not heretofore been easily applied. It will be noted that in this particular instrument the necessary resistance

in the pressure coil circuit is that of the coil and suspenion, 90 ohms and the 54 ohms of the compensator. The total needed for use on 110 volt circuits is 15400 ohms. So the minimum range of the compensated instrument is about 1 volt.

Frequency error,

The dynamometer type of instrument has an inherent error due to the increase in impedance with frequency in the pressure coil of a wattmeter, or in the entire winding of a voltmeter. Except for very low voltage ranges, this error is entirely negligible since the resistances of these circuits are small compared with the resistances ordinarily included in them. It is interesting to note that the compensating device described above for eliminating the phase angle error will reverse the frequency error.

Chamber error,

All electrical instruments are likely to show some change in constants with change in the temperature of the instrument. The major cause is usually change of resistance of the copper conductors. This error may be expected when only a small amount of resistance is used in series with the pressure coil, or coils.

Any wattmeter will give an incorrect reading as commonly used because, either the pressure coil measures the voltage across the load plus the voltage across the current coil, or the current coil measures the current used by the pressure coil. In the instrument here described, the pressure coil takes about .01 ampere and the current coil 5 amperes at full load. This would give 1/5th of 1% error at unity power factor, or 1% if the power factor were .2, or 10% if the power factor is .2 and the load only ½ ampere. This error is easily cancelled by leading the pressure coil current through a stationary coil with the same number of turns as the main current coil but with the current flowing in the opposing direction. These correction turns must be placed close beside the main current coils. This precaution is more important when the current coil is wound for a low current range. In ordinary measurements which involve large load current values, either with or without current transformers, this source of error becomes absurdly small.

Errors resulting from deflection.

In any instrument in which one member rotates with respect to another in order to give the indications desired, two classes of errors are possible. First, the scale and pointer system by means of which readings are secured, will in general require the use of a correction curve, or the scale graduations may be placed in accordance with actual standardized readings. In the instrument here described the errors resulting from using an ordinary equidivision scale were made negligible by curving the scale to a radius equal to 1.6 times the distance from the moving mirror to the center of the scale, (an old rule) and by so building and using the instrument as to keep the maximum deflection down to a small angle (7°) and by so placing the stationary coils of the instruments that the moving coil will move in a very uniform magnetic field.

Second, when the coils of an electrodynamometer wattmeter are not at right angles an electro-motive force will be induced in the moving coil by the current (if a. c.) in the stationary coil. This emf. will be ninety degrees out of phase with the current which induces it but may cause an effect on the deflections unless the pressure coil circuit is non-conductive. This error is always quite small when the pressure coil circuit has a large non-inductive resistance in series with it as is usually the case. It is to be noted that the compensation described above for phase angle error also eliminates the error here described.

The sensitivity of an instrument of this type is determined first, by its ability to definitely respond to a small deflecting torque; and second, by the degree to which the observer can detect this response.

The instrument herein described was so constructed that the weight of the suspended coil was very small. The bifilar type of suspension makes for reliability of return to zero, while sensitivity is obtained by long suspension, narrow separation, and light weight.

The optical system, by which deflections were read, was constructed to provide for an effective pointer of the greatest practical length. As constructed, it measured 407 centimeters long. The system employed was similar in principle to that used in the or-

dinary galvanometer. The scale measured 50 centimeters in length with millimeter sub-divisions and with the telescope used, these subdivisions can be estimated to tenths of a millimeter. This makes it possible to read to one part in 5000, or 2/100ths of 1% of full scale.

Due to the bifilar type of suspension used, the greatest reliability is obtained in that the imperfect elasticity of the metal of the suspension itself affects the restoring force but very little. Thus the instrument, once set on zero, will return definitely to zero after repeated full scale deflections.

Mechanical design,

The base of the Universal Transfer meter was constructed of marble, for the purpose of rigidity and freedom from warping. All the different parts were attached to this base This type of construction makes a metal frame, or supports, unnecessary, thereby removing the possibility for errors due to eddy currents or stray fields present in instruments having such metal frames or cases

The support for the upper end of the suspension wires was a marble block attached to the marble base of the instrument. To this block were secured the terminals to which the ends of the suspension wires were soldered, and through which electrical connection was made to the suspended coil.

Each field coil, of which there were four, was formed from ¼" copper strip shaped into a rectangle and containing two complete turns each. These coils were each supported in grooves cut in marble blocks and attached to the marble base. This affords a very rigid and permanent support for the field coils and at the same time provides the required insulation. The marble supports for the field coils are secured to the base without metal of any kind, thereby eliminating danger of eddy currents. The distance between coils in each pair is made such as will insure a uniform magnetic field around the suspended coil.

The moving element consists of two coils attached to a supporting frame in such a way that they lie in the same plane with their major axes coinciding with the axis about which the element

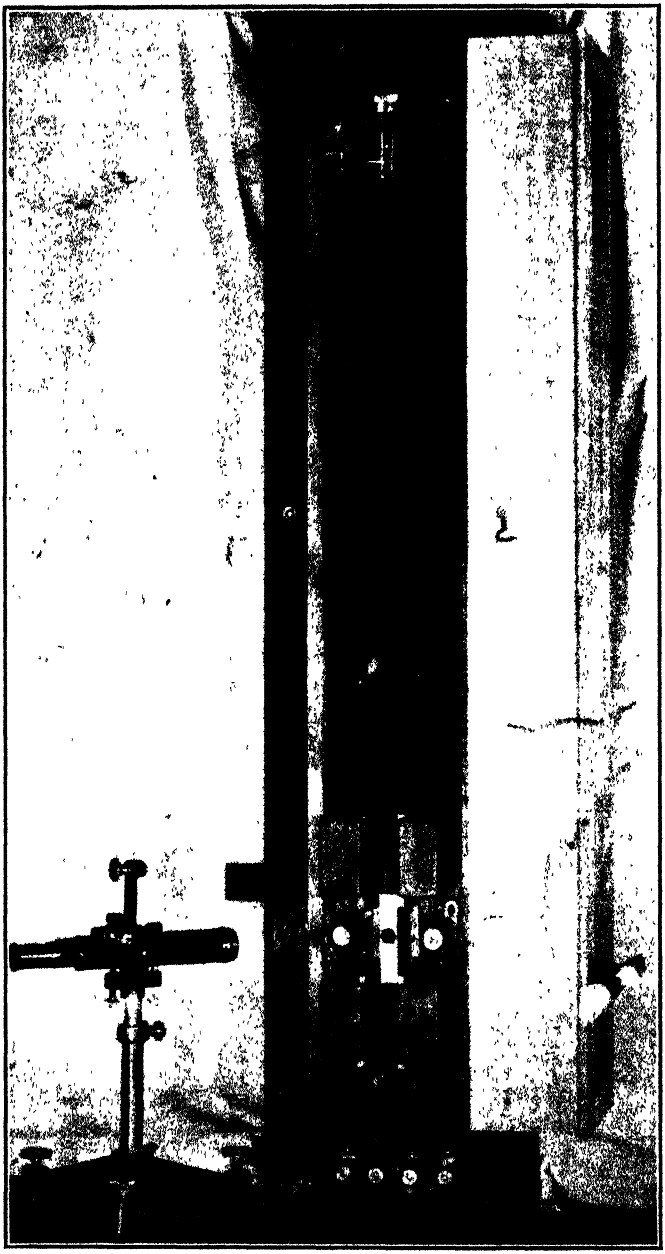

Fig. 2: The meter is shown with the glass covered case opened to expose the details. The scale is above the instrument and is not shown.

rotates when deflected. The coils are of No. 33 D.S.C. magnet wire and are wound to contain 100 turns each. The supporting frame consists of a rectangular paper tube into which one end of each coil is cemented. The terminals are attached to two wires which are fused to a glass spacer and to which are attached the suspension wires. The connection of the two coils in series is such that the circuit represents a figure eight, the magnetic field of one being in opposition to the field of the other.

To the frame of the moving coil system are attached two damping wings, located in the plane of the coils and approximately 1 ¾" on each side of the vertical axis. These damping wings, approximately ⅞" in diameter, operate in air damping cups. Since the maximum angle of deflection is not more than 7°, the damping cups are straight cylinders. If the angle of deflection were greater, these cups would need to be toroidal in shape.

The entire instrument is enclosed in a tight oak case, having a plate glass front. This makes all the working parts visible. For accessibility, the case is hinged to the marble base. To this case is attached the mirror for deflecting the image of the scale into the suspended mirror. Careful provision is made for a special air-tight type of joint between the case and the base, to prevent air draughts from disturbing the moving system within.

It will be seen that the instrument as described can be adapted for use as a voltmeter by replacing the stationary field coils with other coils having a much larger number of turns and connecting these in series with the moving coils In building an instrument for use only as a voltmeter the bifilar suspension should be made with a weaker restoring force, thus reducing the turns needed in the stationary coils.

Fig. 2 shows the appearance of the complete instrument with the case opened so as to disclose the details of the interior.

To use the instrument as an ammeter and insure correct readings on both A.C. and D.C. supply it is necessary to correct the current in the two paths to the same power factor. This was done in the case of the instrument here described by connecting the moving coil system across a circuit made up of one half of the fixed coil system

in series with about a foot of No. 8 copper wire doubled back on itself so as to be non-conductive. The adjustment is made by finding the arrangement that will make the instrument read the same for equal values of alternating and direct current. The equality of these two currents was determined by using a themocouple ammeter as a comparator. The high accuracy attained in the wattmeter and voltmeter can hardly be secured in the ammeter since it will be impossible to avoid relative changes in temperature between the two parallel copper paths. Such changes result in reduced accuracy.

Such an instrument as described affords certain superiorities over other types of electrical instruments now available due to a combination of all the following features:

1. Freedom from pivot errors.
2. Reliability of zero.
3. High sensitivity.
4. Freedom from errors due to stray fields.
5. Compensation to provide accuracy between A.C. and D.C.
7. Adaptability as a voltmeter, ammeter, or wattmeter.
8. Simplicity and ruggedness of construction, requiring no special skill in building.

The accuracy attainable in an instrument of the type described is quite satisfactory. Tests made when used as a wattmeter show the following results:

Stability of zero, within .02 of 1% of full scale, which is the limit of reading.

Largest correction needed at any point along the scale, using the equi-division scale as described, when calibrated with direct current and potentiometers,—.06 of 1% of full scale.

Change in calibration with change in room temperature. .01 of 1% per degree centigrade.

Accuracy of adjustment of phase angle error compensator, within three minutes of arc when using the 3 volt tap.

Reliability of readings,—no deviations among repeated readings were found to exceed .02 of 1%.

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Printed by College Printing Department

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 7 May, 1925 Number 12

SECOND PROGRESS REPORT

ON

The Relation of Road Surfaces to Automobile Tire Wear

By

H. J. DANA

with the advice and assistance of

H. V. Carpenter, H E. Phelps, H. H. Langdon,

W. A. Pearl, and Harry Nash

ENGINEERING BULLETIN No. 17

ENGINEERING EXPERIMENT STATION

H. V. CARPENTER, Director

December, 1925

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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INTRODUCTION

The total estimated highway mileage in all the states of the Union on January 1st, 1925 was 2,866,061. Of this amount there is an equivalent of 31,698 miles of concrete highway 18 feet wide, or 1.1% of the total highway system It may be assumed that there is an equal mileage of bituminous concrete highways, making a total of approximately 63,000 miles of pavement.

The total gasoline tax collected in the United States for 1924 was $77,121,732, and for the first half of 1925, it amounted to $60,108,734 This is in face of the fact that four states, including New York State do not have any gasoline tax

For 1924, the total output in motor vehicles, of all the factories in the United States was 3,650,000. It is estimated that there were 20,200,000 automobiles and trucks in operation in the U. S. in 1925. The revenue from licenses on motor vehicles in 1924 amounted to $222,842,641. The total expenditures on highways in 1924 for construction and maintenance was approximately $1,000,000,000.

In the light of such an enormous investment in motor vehicles and highways, the problems of securing the most economic surface for highway transport becomes of the utmost importance. This problem will be solved when for any particular highway the vehicles using the road and the surface of which it is constructed are such as to produce minimum transportation costs

In making economic comparisons between different road surfaces, consideration must be given both to those costs which arise from the operation of the vehicle and those which arise from the highway itself, in order that the total cost to the owner of the vehicle may be a minimum In most states, at the present time, the automobile owner pays all, or nearly all of the cost of both operating his vehicle and providing the pathway upon which it runs

The former is the result of day to day operation; the latter expense is paid through license and gas taxes. Much research work is being directed toward determining the various items of expense involved in conducting highway transportation, and especially those items that may be influenced in amount by the character of the road surface.

The yearly cost of any road surface depends upon the first cost of that surface, the value of money in that locality, the cost of maintaining the surface under the traffic to which it may be subjected during its economic life and the number of years before the surface requires renewal. The cost of operating a motor vehicle depends upon the cost of oil and gas, tires, repairs, and renewals, depreciation and occasionally other items. Of these items, the cost of gasoline and tires are greatly influenced by the character of the road surface. The effect of the road surface upon gasoline consumption has already been investigated.

During the summer of 1924, a series of tire tests were made on various types of highway surfaces in Washington. The results of these tests were published as a FIRST PROGRESS REPORT in Engineering Experiment Station Bulletin No. 16 of the State College of Washington. These tests were conducted during the summer of 1925 and are submitted herewith as a SECOND PROGRESS REPORT.

It is felt that the facts disclosed by these tests are of such great importance as to justify continuing the research.

The Relation of Road Surfaces to Automobile Tire Wear*

SECOND PROGRESS REPORT

Preliminary to a discussion of the results of the 1925 tests and in order to bring all the test data together and make handy reference possible, a brief summary will be given in Table I and Table II of the Tire Test Data embodied in Bulletin No. 16 for 1924 as compared with the data obtained in 1925. For a full discussion of the 1924 tests, see the above mentioned Engineering Bulletin No. 16.

STATEMENT OF PROJECT

Tire testing has been carried on in one form or another in laboratories for a number of years, but the idea of tests on roads under actual service conditions was first put into practice along the following lines we believe, at the State College of Washington. In conducting a highway test for tire wear, each car was operated over a given road in both directions at a given uniform speed and under conditions of atmospheric temperature as uniform as possible. Care was taken in driving to avoid running over rough places in the road or through moisture, etc. The summer climate of eastern Washington insures a very low humidity necessary for dependable results.

Preliminary to the test, the tires and rims were removed from the wheels and thoroughly cleaned with a brush and bellows. The valve core was then removed and the deflated tire with the rim weighed on a sensitive metric balance. The valve cores were then replaced and the tire pumped up to the necessary pressure and replaced on the wheel.

*We wish to express our appreciation of the continued interest and helpful suggestions contributed by Mr. F. W. Guilbert of Spokane, representing the American Automobile Association, and by State Senator F. J. Wilmer of Rosalia.

Table I. Summary of Tire Tests for 1924-25

Year of tests	1924	1925
No. cars used in tests	5	4
No. tests made	38	53
No. miles on pavement	257.0	1587.5
No. miles on crushed rock	2566.0	1870.7
No. miles on gravel	0.0	252.4
No. total miles tested	3473.4	3548.2
Speed of tests M. P. H.	15, 20, 25, 30, 33	15, 20, 25, 30
Air temperature range	46.6 to 97°F	60 to 105°F

Table II—Comparative Tire Wear ot 30 M. P. H.

Car Used	Car Wt.	Av. tire wear lbs. per 1000 mi.			Tire wear per ton wt. of car		
		Pavement	Crushed Basalt	Water worn gravel	Pavement	Crushed Basalt	Water worn gravel
1924							
5	3750	——	.5117	——	——	.2390	——
6	3160	——	.3333	——	——	.1910	——
3	3690	.0460	.4463	——	.0249	.2221	——
1925							
1	1740	.0477	.2972	——	.0548	.3400	——
2	2750	.0560	.5260	——	.0406	.2940	——
3	3560	.1133	.6616	.4900	.0638	.3000	.2220
4	4400	.1183	——	.6250	.0537	——	.3500

After the test on the highway, the tires were cleaned, deflated, and weighed as at first, and the difference in weight was taken as the measure of the amount of wear which had taken place in the travel of that tire over the distance measured. The speedometers were carefully checked from time to time against marked distances on the highways and against each other.

The temperature of the air was secured from time to time during each run by using a mercury thermometer held out at the

side of the car in such a position as to avoid the influence of heat from the engine.

EXTENT OF PROGRESS

The results of the highway tests conducted in 1924 served primarily to indicate the importance of this field of investigation and to encourage further tests along the same lines. During the summer of 1925 further tests were made in order to determine more definitely the tire wear taking place on pavement such as concrete and bituminous concrete, and to discover if there were an appreciable difference in the wear on each. The tests revealed the fact that tire wear on any good pavement is not the determining factor in tire life; that some other factor, such as stone or rail bruise, overload, or under-inflation, will usually cause tire destruction before the tread has been worn out. But the final failure seldom occurs until the protection given by the tread has been much reduced through wear.

Another angle of the problem of tire wear was undertaken, but has not as yet yielded conclusive results. This involves the question of comparative tire wear as well as gasoline consumption going up and down hill as compared to travel on an average level highway. Table III shows the relative gasoline consumption as derived from tests on two cars.

Table III. Gasoline Consumption on Hills and Levels

Car Used	Car Wt	Gasoline Consumption, Gallons per 1000 mi		
		Down Hill	On Level	Up Hill
2	2750	35.0 gal	51.8 gal.	90.8 gal.
3	3560	36.0 gal.	62 8 gal.	104.8 gal.

Data on Condition of Tires Previous to Tests

Car	Size and Location of Tire	Air Pressure	Age of Tire	Remarks
1	30x3½ front	55	15 mo. 660 mi.	Total mileage during test, 1127 miles. Cord tires all around. Wt of car, 1740 lbs.
	30x3½ rear	55	New 9 mi.	
4	34½x4½ front	65	10 mo. 9000 mi.	Cord tires put on front Dec., 1924, on rear, Feb. 1925. Weight of car, 4400 lbs.
	34 x4½ rear	70	8 mo. 7000 mi.	
3	34 x 4 front	65	18 mo. 10000 mi.	Cord tires. Rear tires moved to front on last two runs. Wt. of car, 3560 lbs.
	34 x 4 rear		10 mo. 6000 mi.	
3	34 x 4 front	65	11 mo. 8000 mi.	
	34 x 4 rear		2 mo. 1100 mi.	
2	32½x3½ front	55	R. F. 2 yrs.	Cord tires. Wt. of car 2750 lbs.
	33 x4 rear	55	L. F. New	
			R. R. New	
			L. R. New	

Highways on Which Tire Tests Were Made in 1925

Location of Highway	Kind of Surface	Length of Test Road	Distance Run	Remarks
Pullman to Palouse	Macadam	16 mi.	65 mi.	Crushed basalt, some corrugations, loose material on surface, few 5% grades, level for most part. Road about 30 feet wide, some curves, dirt shoulders. No rains during tests. Frequently planed by maintenance crew. Two round trips constitute a "run".
Pullman to Lewiston	Macadam	35 mi.	70 mi.	Crushed basalt, some rough places and loose material. Easy curves and grades, dirt shoulders, loose gravel at edges of road. Lewiston hill 8 miles long and average of less than 5% grade. Several hairpin curves on grade. Temperature variation 10 to 15 degrees during day. Speed 20 M. P. H. Required all day for one test. Test down hill, up hill, and on level highway.
Dishman to Coeur d'Alene	Concrete	36 mi.	150 mi.	Concrete in very good condition, in some places worn smooth, oily from oil dripped from passing cars. No grades worth mentioning, easy curves. Traffic not very heavy Two round trips per test.
Dishman Southward 10 miles	Macadam	10 mi.	80 mi.	Crushed basalt, medium size, some loose gravel on surface, easy curves, some easy grades. Very little washboard, dusty, smoother worn track in middle of road. Forest along part of route. Several rail crossings.
Portland to Gresham	Bitulithic	22 mi.	117 mi.	Columbia River Highway, Bitulithic in good condition. Some oil on surface, several easy curves and grades. Road crowned a reasonable amount. Turning out seldom requires travel on dirt or gravel shoulders. Forest along part of route. Test run both ways.
Little Rock to Centralia and to Elma	Gravel	67 mi.	67 mi.	Water worn gravel mixed with sand and clay forming reasonably fine road with rounded gravel protruding from surface. Test run one way.
Olympia to Vancouver and return	Concrete	120 mi.	120 mi.	Concrete with average level grade. Some easy curves and grades. Dirt shoulders. Concrete in good condition. Forest along part of route. All in good repair. One test going up, second returning.

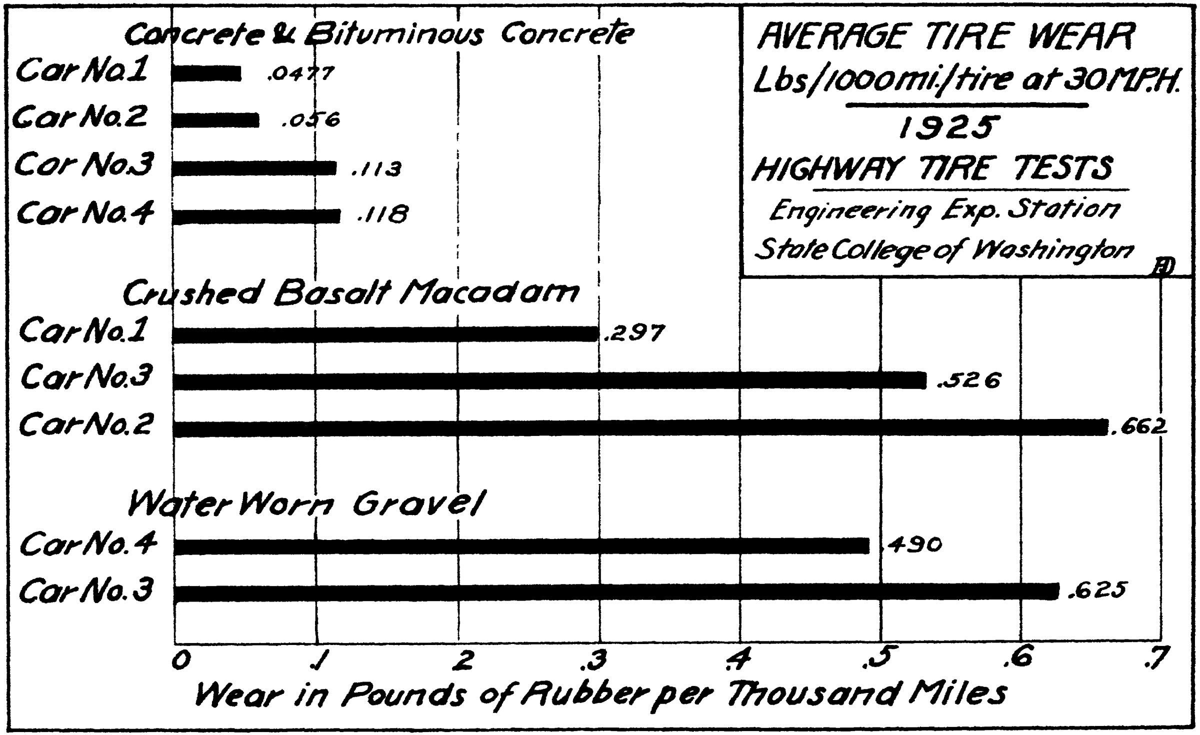
Note on above—Grades on Macadam Roads are not above 5% in any case.

Tire Test Data

Test No.	Car	Route	Type of Road	Speed Miles per Hour	Air Temperature	Grams Wear on Each Tire R F	L F	R R	L. R.	Grams Average Wear	Tire Wear lbs. per 1000 Miles	Total Miles Each Test
2	1	Pullman to Palouse	Macadam	25	92.0	13.4	9.3	17.4	17.3	14.3	.542	61.1
5	”	and return	”	25	81.0	8.5	7.3	5.8	7.1	7.2	.271	60.0
7	”	”	”	30	84.2	6.5	7.7	14.2	10.6	9.5	.360	60.0
19	”	”	”	20	88.0	10.3	8.0	15.8	10.0	11.0	.418	59.6
21	”	”	”	20	88.0	11.0	7.0	10.3	17.0	11.4	.433	60.0
23	”	”	”	30	94.5	4.1	5.2	8.3	11.4	7.2	.275	61.3
25	”	”	”	15	78.0	9.4	6.4	11.2	9.0	9.0	.343	60.4
34	”	Dishman South ten	”	30	81.3	7.5	5.2	14.5	15.3	10.6	.290	80.4
40	”	miles and return	”	30	94.0	6.5	4.0	12.2	13.2	8.9	.244	80.9
36	”	Dishman to Coeur	Concrete	30	81.0	0.9	0.6	0.9	6.9	2.3	.0325	157.0
38	”	d'Alene and return	”	30	86.0	—	—	5.9	3.1	4.5	.0629	157.5
8	2	Pullman to Spokane and return	Macadam	30	97.0	44.2	61.8	74.4	66.3	61.7	.590	169.0
11	”	Pullman to Lewiston Hill	”	20	88.5	13.9	15.4	5.4	11.6	11.6	1.122	23.3
17	”	Lewiston Hill to Pullman	”	20	83.5	5.6	17.1	12.0	7.9	10.6	1.045	23.6
27	”	Pullman to Lewiston Hill	”	20	80.5	8.8	21.1	17.1	14.2	15.3	1.456	23.5
33	”	Lewiston Hill to Pullman	”	20	92.5	7.2	5.0	.7	4.9	4.4	.435	24.9
35	”	Dishman South ten miles and return	”	30	81.3	23.2	23.7	26.3	17.2	22.6	.618	80.4
41	”	”						38.7	27.8	28.6	.777	80.9
37	”	Dishman to Coeur	Concrete	30	81.0	8.9	18.7	1.2	7.6	5.9	.076	170.3
39	”	d'Alene and return	”	30	86.0	—	—	2.6	—	2.6	.036	157.5

Tire Test Data (Cont.)

Test No.	Car	Route	Type of Road	Speed Miles per Hour	Air Temperature	Grams Wear on Each Tire R F	L F	R.R	L R.	Grams Average Wear	Tire Wear lbs per 1000 mi.	Total Miles Test Each
1	3	Pullman to Palouse	Macadam	25	92.0	31.6	10.6	19.1	35.2	24.1	.911	61.1
4	"	and return	"	25	81.0	28.1	15.2	12.6	16.8	18.2	.271	60.0
6	"	"	"	30	84.2	28.8	9.1	10.3	13.2	15.3	.573	61.1
9	"	Pullman to Spokane and return	"	30	94.0	—	30.2	16.1	—	23.1	.308	200.0
18	"	Pullman to Palouse	"	20	98.0	21.2	29.6	20.9	30.1	25.4	.965	59.6
20	"	and return	"	20	88.0	12.3	11.7	17.8	13.9	13.9	.528	60.0
22	"	"	"	30	94.0	—	10.6	26.0	19.5	18.4	.697	59.9
24	"	"	"	15	79.0	4.3	4.8	15.8	22.9	11.9	.453	59.6
42	"	Olympia to Vancouver	Concrete	30	65.0	3.9	5.0	9.4	6.4	6.2	.1136	120.0
48	"	Vancouver to Olympia	"	30	70.0	4.1	6.3	5.5	4.7	5.1	.0960	117.8
44	"	Portland to Gresham	Blacktop	30	63.0	2.3	4.5	6.4	8.4	5.4	.1020	117.0
46	"	am and return	"	30	75.5	4.0	7.2	7.9	10.5	7.4	.1890	114.1
50	"	Little Rock to Centralia	Gravel	30	64.0	14.7	—	25.0	22.5	20.7	.723	67.4
52	"	Centralia to Elma	"	30	64.0	11.7	6.8	16.9	12.1	11.9	.527	58.7
43	4	Olympia to Vancouver and return	Concrete	30	65.0	16.5	14.0	7.4	8.3	11.5	.208	122.0
49	"		"	30	70.0	1.2	0.5	3.7	7.0	3.1	.057	119.0
45	"	Portland to Gresham	Black Top	30	64.0	2.4	10.2	7.0	6.0	6.4	.117	120.4
47	"	am and return	"	30	75.5	2.4	2.2	8.0	6.3	4.7	.091	114.9
51	"	Little Rock to Centralia	Gravel	30	64.0	5.6	4.4	26.6	24.8	15.3	.533	67.6
53	"	Centralia to Elma	"	30	64.0	7.4	7.0	9.9	16.1	10.1	.447	58.7



AVERAGE TIRE WEAR
Lbs/1000mi./tire at 30M.P.H.
1925
HIGHWAY TIRE TESTS
Engineering Exp. Station
State College of Washington
Concrete & Bituminous Concrete
Car No.1 .0477
Car No.2 .056
Car No.3 .113
Car No.4 .118
Crushed Basalt Macadam
Car No.1 .297
Car No.3 .526
Car No.2 .662
Water Worn Gravel
Car No.4 .490
Car No.3 .625
0 .1 .2 .3 .4 .5 .6 .7
Wear in Pounds of Rubber per Thousand Miles

Fig. 1

In Figure 1 is shown the results in average tire wear per tire of the highway tests made in 1925. These tests were made at a speed of 30 miles per hour over highways which were selected for uniformity in grade and surface.

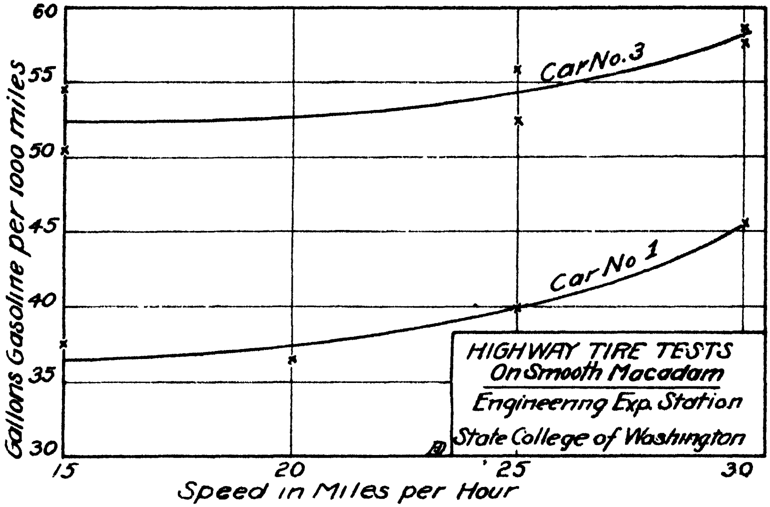


Fig. 2

Figure 2 shows the average gasoline consumption of two of the cars used in the highway tests operated over a road which is almost level and in excellent condition. It will be understood that the gasoline consumption of a car depends not only upon the speed at which the car is driven but among other things upon the condition of the engine, adjustment of the carburetor, timing of the ignition, etc. However, the relation of gasoline consumption to speed as shown is more or less characteristic of cars of the weight used in these tests, irrespective of make.

Fig. 3 represents the results of tests made on the Lewiston Hill in Idaho. The section of the hill used for the tests is eight miles long with an average gradient of 4.2% and not to exceed 5% at any point. The cars were driven at a speed of 20 miles per hour. Going down hill, the engine was left in gear and whenever necessary, the brakes were applied as lightly as possible to keep the speed

// MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

❦ ❦ ❦ PULLMAN, WASHINGTON ❦ ❦ ❦

Vol. 10 | August, 1927 | Number 3

MAGNETIC NAIL PICKER FOR HIGHWAYS

by

H. J DANA

ENGINEERING BULLETIN No. 21

ENGINEERING EXPERIMENT STATION

H. V. CARPENTER, Director

Entered as second-class matter, September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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MAGNETIC NAIL PICKER FOR HIGHWAYS*

INTRODUCTION

There are between twenty-two and twenty-five million passenger cars registered in the United States for 1927. It is the common experience of every motorist that their tires all too frequently pick up some object from the highway surface which causes a puncture or blowout. This object is usually a piece of iron either in the shape of a tack, a nail, a bolt, or something similar. Such a puncture not only results in a loss of time and annoyance to the driver, but results in serious damage to the casing and the tube of the tire itself, and sometimes leads to serious accidents. In view of the commonly recognized need of relief in this matter it is highly important that some steps be taken to remove, or at least reduce, this cause of expense and trouble to the motorist.

The object of the following work is:

First: To develop a suitable equipment for magnetically removing iron from the highways.

Second: To determine the amount of dangerous iron which is on different types of highways.

DESCRIPTION OF TYPES OF MAGNETS

A number of different types of magnets have been used more or less successfully for the purpose of removing iron from highways. Current for such magnets is derived either from a storage battery or from an engine-driven generator. Where a storage battery is employed as the source of current the magnet must necessarily be operated very close to, if not in contact with, the road surface itself because the amount of pull which it is possible to obtain from a battery energized magnet is very limited unless a very large and heavy battery is employed.

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* Complete detail drawings and specifications for building highway magnets according to the current supply available may be had for $5.00 per set by addressing Director, Engineering Experiment Station, State College of Washington, Pullman, Washington.

These magnets sometimes take the form of a "U" shaped piece of iron on which is wound a quantity of magnet wire. The horseshoe type of magnet for this kind of work has an inherent weakness in view of the fact that the magnetic flux not only crosses the air gap between the two tips, but also crosses between the legs of the magnet as well. Since the useful flux in a magnet for use on a highway is only that portion which extends from the magnet tips down to the road surface, any other flux generated by the magnet coil, and which does not reach the road surface, represents a waste of power. It will, therefore, be apparent that the effective power of a horseshoe type of magnet used for highway work can never be more than a small proportion of its total power.

A design of horseshoe type of magnet has been employed by some highway departments in which the coil was located well up on the magnet leg so that the tips of the magnet core might be permitted to drag upon the road surface. In this way a series of such magnets with their pole-tips dragging along the road surface would come into very close contact with any particle of iron lying there

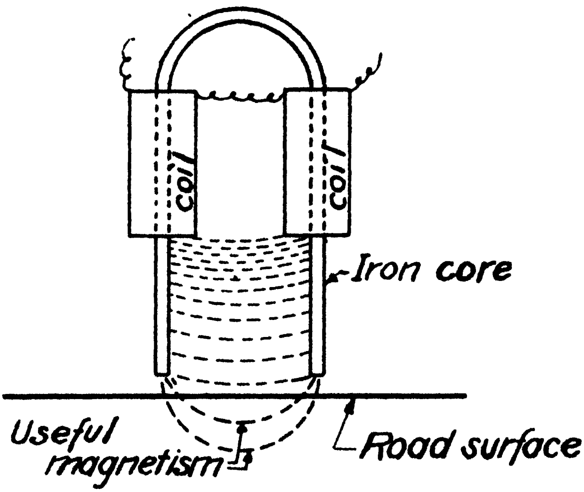

Fig. 1

and would pick it up. Such a magnet is illustrated in Fig. 1. This type of magnet must be operated very slowly over the highway and must be frequently cleaned, otherwise iron particles collected will be dragged away and left to remain on the road surface.

A more suitable design for a magnet for this purpose is shown in Figure 2. It will be seen from the illustration that practically all of the magnetic flux of this type of magnet dips down into the surface of the highway and is useful in attracting the iron from the highway. In a general way this is the design of magnet employed for lifting in the steel industries and has been found to be the most efficient type for such kinds of work.

There are several items which enter into the design of a magnet for picking iron from the highways. First to be considered is the speed of operation at which it is desired to use the magnet. The most satisfactory speed on an open highway seems to be about eight to fifteen miles per hour. In city streets and alleys about three to ten miles per hour is most satisfactory, depending upon the roughness of the roadway. Second, at the above speeds the magnet must necessarily be suspended some two or three inches above the highway surface. This means that the magnet must be strong enough to give a very definite and substantial pull on any iron lying on the surface of the road and must be able to lift it from the ground during the brief interval the magnet is travelling past. It is therefore important that the magnet have as large a magnetic pull as possible, such magnetic pull being determined by the number of turns of wire in the coil and the number of amperes of current flowing through this wire, in other words, "ampere-turns". The size of the current which a coil of wire can carry is determined by the size of that wire and the ability of the magnet to radiate the heat caused by the passage of the current through the wire. The number of ampere-turns which can be used on a given magnet core are determined by the size of wire used and the available space for winding. One can use a small current through a great many turns of wire, or a large current through a small number of turns, keeping the ampere-turns the same in each case, and derive the same magnetic pull from each magnet. In either winding the same magnetic pull requires about the same amount of copper. However, the smaller wire requires that

a larger proportion of the winding space be taken up with insulation than is the case where a large wire is used.

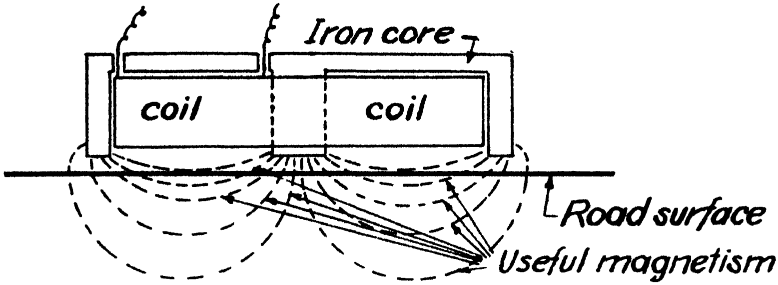

Fig. 2

Experience has shown that an engine driven generator furnishes the most satisfactory source of current for a highway nail picking magnet. In a few instances use has been made of a commercial lifting magnet swung underneath a truck and supplied with current from a gas engine driven generator carried on the truck. While such an outfit is very satisfactory as far as strength and speed of operation is concerned, the area covered by each magnet, namely, a strip twenty to thirty inches wide on the highway requires many trips in order to cover the entire width of the road In view of the fact that these magnets are designed for lifting power at a concentrated point, and in view of the fact that a highway magnet should have its pulling power distributed efficiently over a considerable width of road the commercial type of magnet is not an economical device for extensive use. In order to make the nail picking operation an economical one the apparatus should be designed to cover the entire road surface in one round trip It was with the above points in mind that the following described magnetic nail picker was designed and built at the State College of Washington.

POWER PLANT

The power plant consists of a Ford engine equipped with a

large radiator and a circulating pump and mounted on a set of skids. Direct-connected to this engine is a three kilowatt 110 volt direct current generator. Suitable throttle control is provided for on the engine so that the speed can be adjusted as desired. An automobile type of ammeter mounted on the generator indicates the amount of current being used in the magnets and a field rheostat gives suitable control. This makes a self contained power plant which can be readily loaded on any suitable truck. Heavy steel handles are bolted on the skids for use in handling the outfit on and off of the truck. It was found that the most satisfactory speed for the engine and generator was about 800 R. P. M. The relation of speed to power of the Ford engine is such that no speed governor is necessary since the power required by the magnets increases rapidly as the generator speeds up. Therefore the engine will operate practically at a constant speed depending upon the throttle opening.

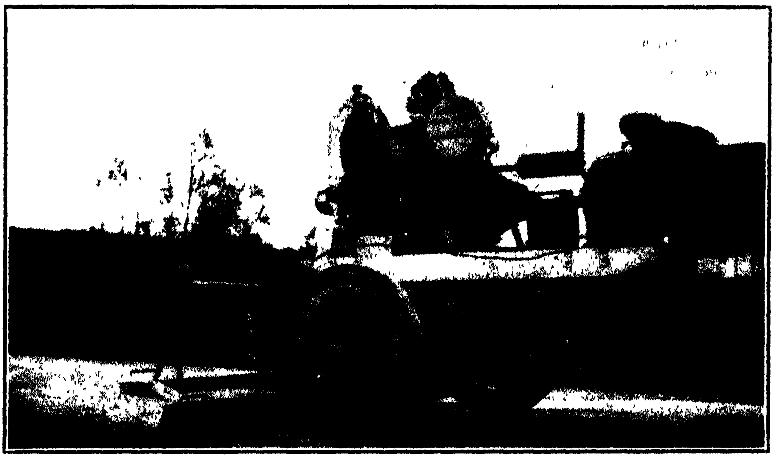

Figure 3

MAGNETS

The magnets were designed in sections four feet long. This makes it convenient to use either one, two, or three magnets as conditions of width and roughness of the highway would seem to make it desirable. The core of each magnet consists of a 12″ "I-beam"

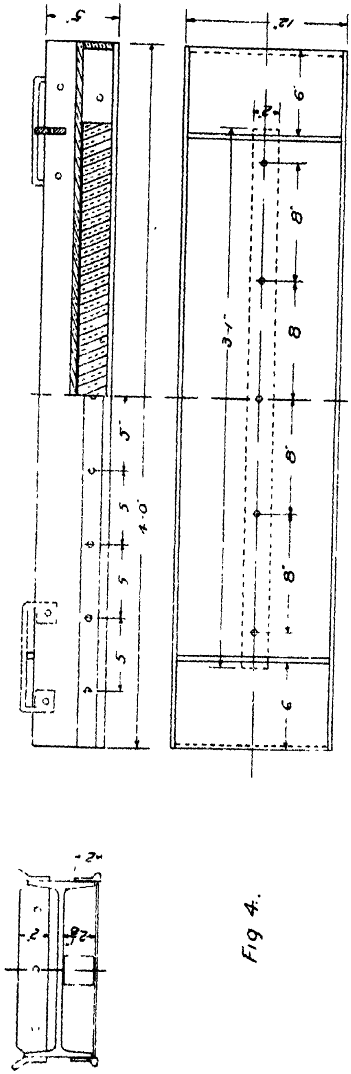

Fig 4.

four feet long, to the center of one side of the web of which is bolted a 2″ x 2″ square bar of iron as shown in Fig. 4. This type of construction results in a coil laid in one side of the I-beam and surrounded on all sides but one by iron. Over the open side of the coil is bolted a sheet of brass to protect it from injury as it passes over loose rocks on the highway surface. This brass plate also provides protection to the coil from pieces of metal drawn up to it. On the opposite side of the I-beam are welded two strips of steel with holes for supporting chains extending upward to supporting mechanism on the truck body. Four heavy steel handles are provided on each magnet for ease of handling. This is necessary in view of the fact that each four foot section of magnet weighs nearly four hundred pounds. The magnet winding consists of 315 turns of No. 7 double cotton covered square magnet wire. The complete coil, weighing about 200 pounds, was thoroughly impregnated with insulating compound. Before the coil was laid into the magnet yoke the inside of the yolk was painted with varnish and insulated with two layers of thick paper. After the coil was mounted in the core two layers of the same paper were placed over it and secured in place by the heavy brass protecting plate. This brass plate extending over the entire surface of the magnet not only retains the coil in place, and affords protection from injury, but facilitates the removal of the collected iron when the current through the magnet is turned off. If the collected iron were in contact with the iron surface of the magnet core it would not so readily drop off when the current is turned off.

The winding of each magnet was designed for thirty amperes continuous operation. If two magnets or more are used together they are to be connected in series, thereby demanding thirty amperes of current from the generator under all conditions. In use the magnets are suspended with the front edge about two inches above the road surface and the rear considerably higher as shown in Fig. 5. This prevents accidental contact with the road from brushing away accumulated material on the face of the magnet. Owing to the fact that the leading edge of the magnet frequently comes into contact with rocks, or with the surface of the road itself, a steel reinforcing strip is bolted to this edge in order to take the blows and sustain the

wear. This strip can be renewed whenever necessary. A like strip on the rear edge of the magnet makes it possible to turn the magnet around and operate it in the other direction. The terminals of the coil extend through insulated holes in the web of the I-beam to a

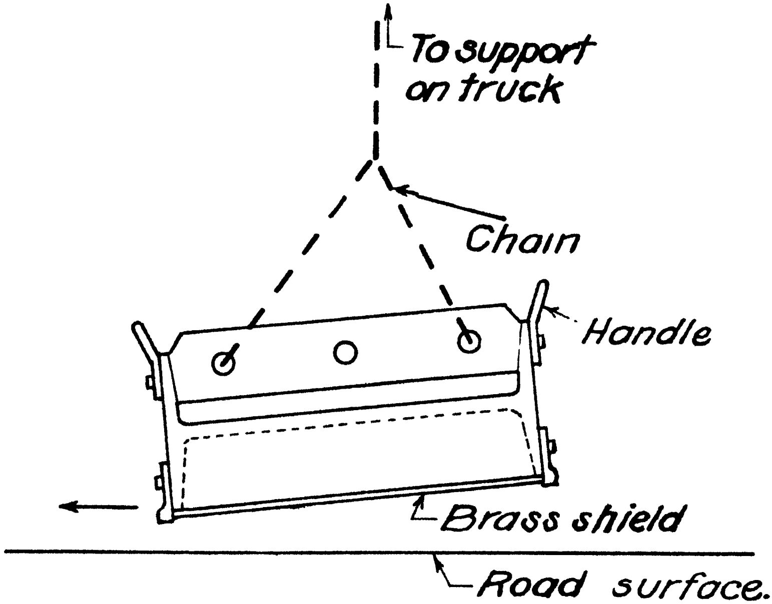

Fig. 5

terminal block on the upper side. These insulated holes are thoroughly sealed with insulating compound in order to prevent the entrance of moisture into the coil. At 30 amperes the power consumed by each magnet is approximately 900 watts.

Operation of Magnetic Nail Picker on the Highways

The following are the requirements for successful operation of the nail picker in collecting iron from the highways:

The power plant should be loaded on a two or three ton truck. The desired number of magnet sections, not to exceed three, should

be suspended beneath the truck. It is preferable to suspend these magnets just in front of the rear wheels. Where three magnet sections are employed the center section may be suspended under the center of the truck immediately behind the rear wheels. The two outside sections slightly lapping over the area covered by the center magnet may be suspended from a cross timber or pipe attached to the truck body, preferably in front of the rear wheels. The three magnets should then be connected in series to the generator and the current adjusted to 30 amperes. Figure 6 shows the outfit employing but two magnets.

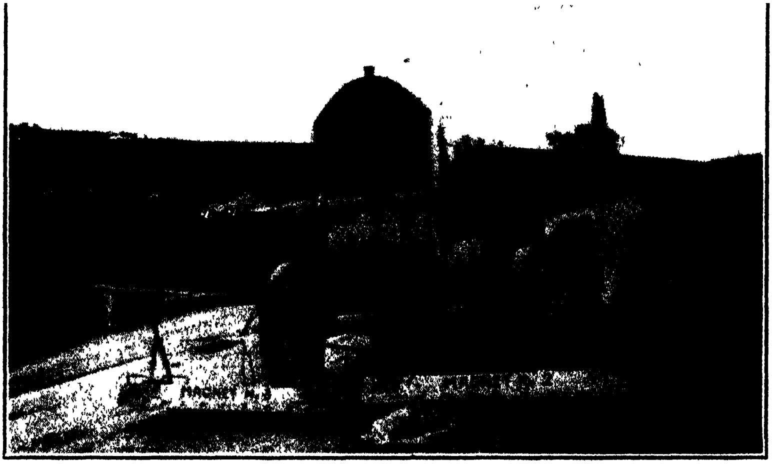

Figure 6

Two men are ordinarily required for the operation of the nail picker until the operation is well understood when one man can handle it successfully alone. One drives the truck in such a way that the magnets cover an area to the right of the center of the road. The width of most highways is such that the right hand magnet will extend over the shoulder of the road. The truck is driven at a suitable speed, say from eight to fifteen miles per hour. While the outfit is moving, the second man can do little but see that the power plant continues to furnish the required amount of current to the magnets. The collected iron should be cleaned from the magnet frequently since too great an accumulation reduces the useful strength

of the magnet. For the cleaning operation the truck is stopped and a piece of canvas is spread underneath the magnets. Then either by means of opening a switch or by stopping the engine, the current is cut off allowing the accumulated iron to drop onto the canvas. This iron should be preserved as evidence of the condition of that stretch of highway. It is desirable at some time to weigh this iron and determine the amount per mile collected. It will be found that the largest proportion of iron will usually be collected from the edge and the shoulder of the road. However, there will be a very appreciable amount also collected from the center of the road where traffic is heaviest. Figure 7 shows one of the magnets turned up on edge to show the nails and iron accumulated while operating over an area used for parking cars where a quantity of old lumber had formerly been piled.

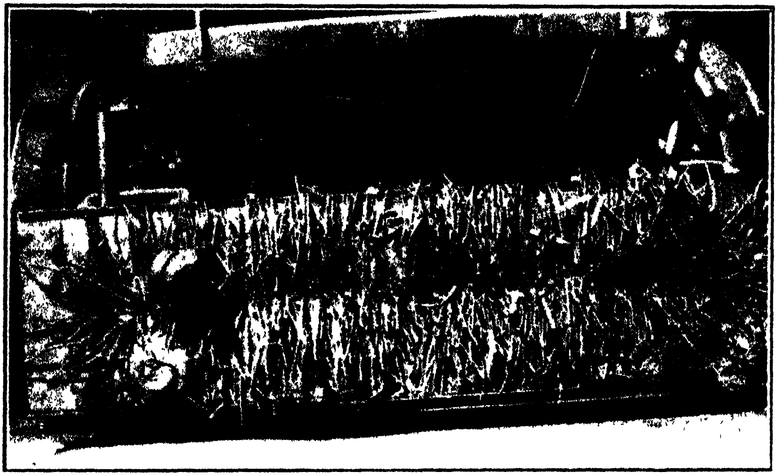

Figure 7

The cost of operation of this outfit will be that of the truck plus the gasoline and oil used by the power plant plus the wages of the one or two men employed.

Results of Tests

In the operation of the nail picker over the highway it was discovered that the amount of iron per mile collected was about uniform.

A mile of highway adjacent to a city contains about the same amount of iron as a mile of highway ten miles from the city. It was found, however, that at least three-fourths of the iron is located at the edge of the road. The iron picked up from the center of the road, however, in most cases consists of small nails and tacks, all of which are definite sources of tire trouble. The iron collected from the edge of the road contains many items such as nuts, pieces of bolts, broken pieces of spring leaves, etc., which do not materially endanger a tire. It is estimated that at least three-fourths of the material collected is a definite menace to automobile tires. Figure 8 shows three piles of material accumulated in tests made on the loose crushed rock highways in Whitman County, Washington. The average motorist would strongly object to driving his car over any of these three piles but he drives over the same material every time he uses the highway.

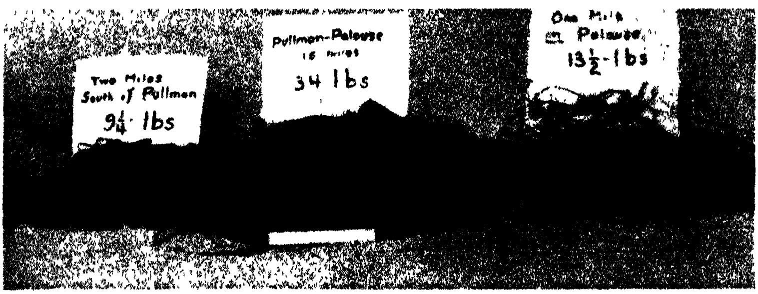

Figure 8

Economic Conclusions

On highways, on city streets, and in alleys, automobile tires pick up particles of iron which sooner or later result in a puncture or a blow-out. Each puncture not only damages the tire, costs money to repair, and furnishes annoyance to the driver, but is often the cause of a serious accident. This iron accumulates on the road surface from wagon beds, trucks, car bodies and merchandise hauled over the roads. There is no reason to expect that the deposit of this material on the highways can be prevented. It therefore remains for some means to be used to remove it as often as it seems desirable.

The cost of one man with truck and nail picking equipment per day will amount to about twenty to twenty-five dollars. One outfit should be able to travel at least sixty miles per day. This will represent the clearing of both sides of a road thirty miles long each day. It is estimated that two trips per year over a gravel highway would be sufficient to remove the accumulated iron. Balanced against this cost of clearing the highways is the total cost to the motorists in money for repairing punctures, in time lost to change tires, in annoyance at the delay, and in real danger of accident confronting a car which has a puncture while traveling at high speed. These items can only be approximated in money value, but it is commonly agreed amongst motorists that this would far exceed the cost of removing the iron from the highways. It will, of course, be understood that it would be impossible to permanently or completely remove all sources of tire puncture from the highway because the distributing process is continuous and a nail picker can only reduce the chances for puncture and not entirely eliminate them. However, the lessening of danger of accident to life and property will well repay the nominal cost of operating such a machine over alleys, streets, and highways once or twice per year.

Engineering Bulletins
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   By O. L. Waller and M. K. Snyder, March, 1914, July, 1916.
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   By O. L. Waller, October, 1915, Reprint 1925.
3. Water Supply for the Country Home. (Out of Print.)
   By M. K. Snyder. See Eng'rg. Bul. No's. 9, 10, and 11.
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17. Relation of Road Surface to Automobile Tire Wear. Second Progress Report. By H. J. Dana, December, 1925.
18. Relation of Road Surface to Automobile Tire Wear. Third Progress Report. By H. J. Dana, October, 1926.
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21. Magnetic Nail Picker for Highways.
    By H. J. Dana, July, 1927.

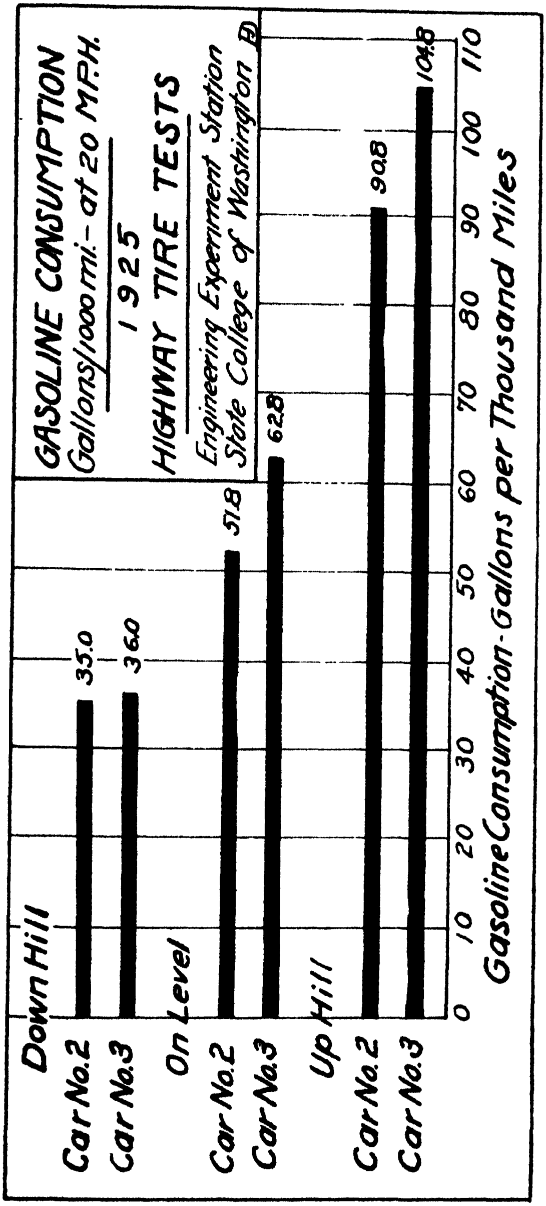
GASOLINE CONSUMPTION
Gallons/1000 mi.- at 20 M.P.H.
1925
HIGHWAY TIRE TESTS
Engineering Experiment Station
State College of Washington
Down Hill
Car No.2
Car No.3
On Level
Car No.2
Car No.3
Up Hill
Car No.2
Car No.3
35.0
36.0
51.8
62.8
90.8
104.8
0
10
20
30
40
50
60
70
80
90
100
110
Gasoline Consumption - Gallons per Thousand Miles

Fig. 3

down to 20 miles per hour. The gasoline consumption down hill represents what the engine used with a closed trottle and a carburetor adjustment for normal every day driving, or in other words, an idling condition and possibly at more than idling speed. It will be understood that a special adjustment of the carburetor could have been made which would have greatly reduced the consumption of fuel down hill, but this would not then be considered normal practice in driving. The twenty-three miles of highway on which were run the tests for the data "on level" of figure 3 cannot be compared with the level highway represented by figure 2. The former is also macadam but not in first class condition, and extends over a low rolling country.

Table IV. Relative Fuel Economy

Car Used	Gasoline Consumption, Gallons per 1000 mi					Difference in Cost Gas @ 25c
	Down	Up	Ave	Level	Diff	
2	35	90.8	62.9	51.8	11.1	$2.77
3	36	104.8	70.4	62.8	7.4	1.85

Table IV shows the relative fuel economy of travel over hilly roads as compared with travel on a practically level highway, based on the same distance traveled up hill as down. This at once gives rise to the question of the expense to the motorist of traveling a hilly highway, and of the desirability of going to the expense of rebuilding the highway to eliminate the grades. Comparative gasoline consumption is but one item—another being comparative tire wear. Added wear and tear on the car mechanism would also be an item worth considering, as well as comfort in motoring.

From Table IV, it will be seen that when considering gasoline alone, travel over a highway in which it would be possible to eliminate hills is costing the motorists from $1.85 to $2.77 extra per thousand miles, according to the results of the above tests. It may be interesting to note from Fig. 3 that if a motorist coasted down all hills with the motor stopped, assuming that he traveled as far up hill as down, he could travel a given distance cheaper than on a level highway where the engine is working at much less than full

capacity. However, such is not the practice with the motoring public and could not be used as a basis for comparison.

THE ECONOMIC SIGNIFICANCE OF HIGHWAY TESTS

The cost to the motorist of using a highway includes such items as gasoline consumption, tire wear, depreciation of the machine, etc. Speed and load limits are also factors which aid in determining the value of a highway. However, since the tests have been confined mainly to the comparative rate of tire wear, the following analysis will be based on the item of tire wear alone.

The average tire wear for a touring car of 3500 to 3700 lbs. weight at an average speed of 30 M. P. H. as determined from the 1924 and 1925 tire tests was 554 lbs. per tire on macadam and .080 lbs per tire on pavement per thousand miles. The total tire wear per car for all four tires in each case would be 2.216 and .320 lbs. respectively, considering standard 33 x 4 tires only. The difference in tire wear per car on the two types of highway will be 1.896 lbs. per thousand miles.

If it be assumed, as in THE FIRST PROGRESS REPORT of 1925, that an average of 3 45 lbs. of tread rubber is worn off in the life of this type of tire, and if the cost of the tire be divided by the amount worn off during its life, the rate will be found to be approximately $10 00 per lb. Then the cost of tires to operate the above car over average macadam roads will be $18 96 per thousand miles more than to operate it over pavement. If the difference in annual cost per mile between pavement and macadam roads be taken again at $501.29, as derived from the Report of the Bureau of Public Roads for 1924, then, on the basis of tire wear alone, it will require a traffic of 26,400 such cars per year or an average of 72 cars per 24-hour day to justify the building of the better road.

The above analysis is based upon the average of a large number of tests on one car. Following is a similar analysis employing the average tire wear as derived from all the tests of all the different weight cars used in the tests of 1924 and 1925. The over-all average tire wear for all cars tested is .463 lbs. per tire on macadam and .103 lbs. per tire on pavement per thousand miles. The total wear

per car in each case would be 1.852 and .412 lbs respectively, considering standard tires only. The difference in tire wear will be 1.440 lbs of rubber per car per thousand miles .

Considering the average of all sizes of pneumatic tires for private passenger cars the amount of tread rubber worn off in the life of the tire will approximate 2½ lbs. At the rate of $10.00 per lb. again, the difference in cost to the motorist for tires alone between travel on crushed rock macadam and on pavement is $14.40 per thousand miles per car. If the difference in annual cost per mile between pavement and macadam is $501.29 as above, then on the basis of tire wear alone, it will require a traffic of 34,800 cars per year, or an average of 95 cars per 24 hour day to justify the building fo the better road.

Using an average first cost for pavement over the entire United States of $30,000 per mile, the difference in annual cost per mile will be justified in the above analysis by 182 cars per day. It should be kept in mind, however, in determining a proper cost for pavement that there is no question of the economy of pavement for roads with heavy traffic. The pavement to be considered here, therefore, should be that chosen for roads with moderate traffic demands.

In as much as the foregoing analysis, as stated above does not include such items as gasoline consumption, depreciation of the machine, comfort in riding, saving of time, etc., the figures submitted above for the number of cars per day needed to justify paving are without doubt considerably in excess of the correct minimum.

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol 9 October, 1926 Number 5

THIRD PROGRESS REPORT

ON

The Relation of Road Surfaces to Automobile Tire Wear

By

H. J. DANA

With the Advice and Assistance of

H. V. Carpenter, H. H. Langdon, R. D. Sloan

O. L. Osburn, J. G. Woodburn,

Geo. Lommasson

ENGINEERING BULLETIN No. 18

ENGINEERING EXPERIMENT STATION

H. V. CARPENTER, Director

December, 1926

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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ENGINEERING EXPERIMENT STATION STAFF

INTRODUCTION

During the summer of 1924, a series of tire wear tests were made on various highway surfaces in the states of Washington and Idaho and the results were published in a **First Progress Report**, Bulletin No. 16. The work was continued in 1925 and the results published in a **Second Progress Report**, Bulletin No. 17. Further tire wear tests on the highways of Washington, Oregon and Idaho, were made during the summer of 1926 and the results are herewith submitted in a **Third Progress Report**, Bulletin No. 18.

Owing to the fact that balloon tires are largely replacing standard tires on passenger vehicles, the two test cars were fitted with balloon tires, and thus equipped, were used in all of the 1926 tests.

THE RELATION OF ROAD SURFACES TO AUTOMOBILE TIRE WEAR

THIRD PROGRESS REPORT*

The results of the tire wear tests made in 1924 and in 1925 do not correspond exactly in value with each other or with the tests made in 1926. This may be attributed in part to the use of different cars and tires over different highways under varying degrees of maintenance. The various variable factors entering into the making of such tests make it necessary to correlate the results on the basis of general averages.

In order to present for comparison the results of all the tests made, a brief resume is given in Table 1 of the conditions surrounding the tests made during the summers of 1924, 1925 and 1926. In Fig. 1 is depicted graphically the results of the tests made on pavement and on crushed rock macadam. For a full discussion of the method of testing and of the results of tests made prior to 1926, see Engineering Bulletins No. 16 and 17.

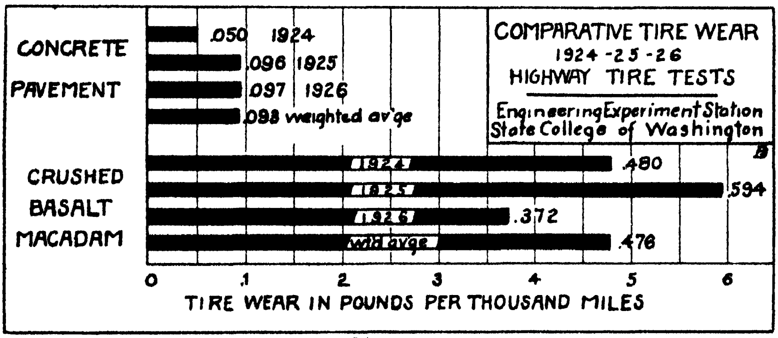

Figure 1

* In 1925 a short test of 460 miles was conducted on bitulithic concrete and a similar test of 480 miles was made on cement concrete pavement in Western Washington and Oregon. The results of these two short tests were .125 lbs. tire wear per 1000 miles for bitulithic and .118 lbs. per 1000 miles for cement pavement. While there is a difference shown between the tire wear on the two types of pavement, this difference is too small to justify any conclusions as to their relative merits.
A short test of 225 miles conducted at the same time on water worn gravel showed an average tire wear of .557 lbs. per 1000 miles.

Table I. Summary of Tire Test Details

	1924	1925	1926
No. cars used in tests	5	4	2
No. tests made	38	53	40
No. miles on pavement	257.0	1587.5	1597.0
No. miles on crushed rock	2566.0	1870.0	2247.0
No. miles on gravel	0.0	252.4	0.0
No. miles on oiled road	0.0	0.0	1804.0
No. total miles tested	3473.4	3548.2	5648.0
Speed of tests, m.p.h.	15, 20, 25, 30, 33	15, 20, 25, 30	20, 30

STATEMENT OF PROJECT

Two identical cars were secured for the tire tests in 1926. These were balloon equipped, Oakland Coaches, weighing 3750 each, with load and driver. Both cars were nearly new and in excellent condition as regards tires, wheel alignment, and 4 wheel brake adjustment These cars were chosen as being about the average in weight.

The method of cleaning and weighing tires was the same as described in previous progress reports from which we quote:—

"Preliminary to the test, the tires and rims were removed from the wheels and thoroughly cleaned with a brush and bellows. The valve core was then removed and the deflated tire with the rim weighed on a sensitive metric balance. The valve cores were then replaced and the tire pumped up to the necessary pressure and replaced on the wheel.

"After the test on the highway, the tires were cleaned, deflated, and weighed as at first, and the differnce in weight was taken as the measure of the amount of wear which had taken place in the travel of that tire over the distance measured. The speedometers were carefully checked from time to time against marked distances on the highways and against each other."

In the case of tests on oiled highways, the tire treads seemed to become glazed with a film of material consisting of oil bound dust presumably derived from wear on the surface of the road itself. As the customary brushing before weighing failed to remove this film, each tire was then subjected to additional cleaning by rubbing with dry waste or cheese cloth until the glaze was removed.

EXTENT OF PROGRESS

The results of the highway tire tests made in 1924 and 1925 were based upon standard tires, operated upon crushed rock and pavement highways. Two new features were introduced in the 1926 tire tests. First, owing to the increasing popularity of balloon tires for pleasure vehicles, this type of tire was chosen and used in all the tests on various types of highways available.

Second, inasmuch as it seems likely that the oil treatment of crushed rock highways will figure extensively in the future highway program of the State of Washington, plans were made for extensive tests on the best oiled highways available.

CONDITION OF HIGHWAYS TESTED

Tests were made on water bound macadam with some loose crushed stone surface, on cement pavement, and on oil treated macadam. The crushed stone road from Pullman to Palouse, Washington was smooth and hard and almost free from loose gravel and corrugations, closely approaching eastern macadam ,except that the stone used is crushed basalt. There are no sharp curves and the grades are long and easy.

The cement concrete highway on which tests were made extends from the top of the hill north of Colfax, Washington northward through Steptoe and about one mile beyond, having a total length of approximately 9 miles, 4 miles of which is 5 years old and 5 miles of which is 2 years old. This highway is in good condition, practically free from motor oil, and is fairly level with no sharp curves.

A suitable length of first class oil treated highway extending from Pendleton to the Dalles, Oregon was used for the tests. A few

HIGHWAYS ON WHICH TIRE TESTS WERE MADE IN 1926

Location of highway	Kind of surface	Length of Test road	Remarks
Pullman to Palouse	Crushed basalt macadam	16 miles	Crushed basalt, no corrugations, very little loose material on surface, few 5% grades, level for most part Road about 30 feet wide, some curves, dirt shoulders. No rains during the tests. Very little crown.
Colfax to Steptoe	Cement Concrete	9 miles	Cement Concrete, two and five years old, very little motor oil on surface, easy grades, no sharp curves, sealed expansion joints every 20 feet and along center of newer portion.
Pendleton to The Dalles	Oil treated crushed basalt macadam	144 miles	Crushed basalt, treated with a heavy oil, followed by an application of sand or crusher "fines", forming a smooth hard surface. Several sharp well banked curves. Easy grades, well maintained, normal amount of crown.
Lewiston Hill	Crushed basalt macadam	8 miles	Crushed basalt macadam, maximum grade of 5%. Several sharp curves. Turns are banked for average speeds of 20 m. p. h. Considerable loose gravel except where it had been whipped off at the curves by passing cars.

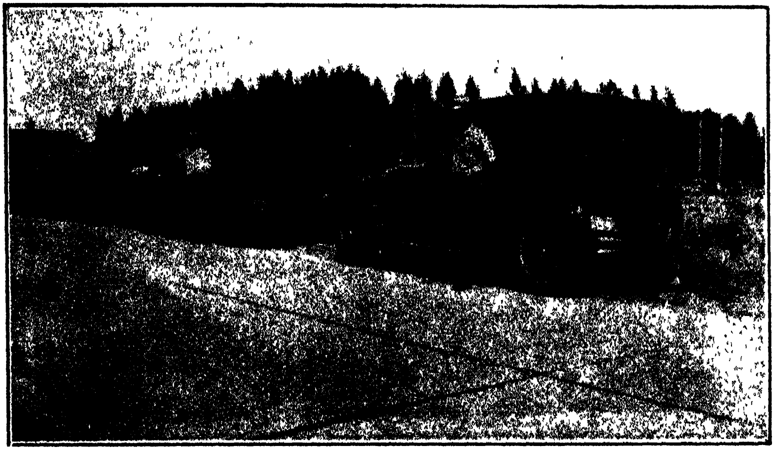

Figure 2. The two tire test cars used for the tests made in 1926. The scene is on the concrete pavement at Steptoe, Washington.

miles of this oiled highway just west of Pendleton has been built and in use for three years, the next portion on through Echo is two years old, and the rest of the highway to the Dalles, is one year old. Several very short sections had been processed and re-oiled during the early summer of 1926. While it was very evident that a recent application o: oil had been made to these sections, no excess of oil was evident on the surface and it was considered permissable to use the entire length of 144 miles from Pendleton to The Dalles for the tests. There are numerous easy grades and a few sharp curves along this route. The surface was exceptionally smooth and free from pitting, due in a large measure, no doubt, to the persistent maintenance methods employed. Figure 3 shows a stretch of oil treated highway north of Stanfield, Oregon.

TIRES

Both cars were equipped when new with 31 x 5.25 cord balloons which were used throughout the tests At the beginning of the tests the tires on Car No. 1 had run 3900 miles and on Car No. 2 1800 miles and were about 4 and 2 months old respectively. The treads showed

1926 TIRE TEST DATA

Test No.	Car No.	Route	Type of Road	Speed M P H	Total miles each test	Grams wear—each tire R F	L.F.	R.R	L.R.	Grams Ave	Wear per tire per 1000 miles
3	2	Lewiston Hill up	Crushed basalt macadam	20	43 4	19.1	16.9	22.2	21.5	19.9	1.01
5	2	Lewiston Hill down	″ ″	20	51.8	13.4	13.3	16.7	15.7	14.8	63
7	1	Pullman to	″	30	98.6	29.4	18.8	19.3	13.8	20.3	.453
8	2	Palouse	″	30	98.9	13.0	13.2	21.2	26.2	18.4	.406
9	1	″	″	30	100.5	16.1	15 9	26.9	29.7	22.1	.487
10	2	″	″	30	102 7	14.9	14.8	17.2	19.3	16.5	.354
11	1	″	″	30	98.7	14.5	13.5	20.9	—	16.3	.359
12	2	″	″	30	98.5	9.5	13 0	20.8	21.5	16 2	.363
13	1	″	″	30	99 9	9 0	7.0	14.1	22.2	13.1	.290
14	2	″	″	30	99.9	11.0	12 2	14.8	7.7	11.4	.251
15	1	″	″	30	102.2	19.8	14.8	26.8	28.9	22.6	.488
16	2	″	″	30	102.2	15.3	19 0	—	37.1	23.8	.514
17	1	″	″	30	293.7	38 9	39.4	52 2	—	43.5	.327
18	2	″	″	30	296.7	31 7	38.2	52.9	65.7	47.1	.350
27	1	″	″	30	199 0	19.4	17.4	31 3	31.1	24.8	.275
28	2	″	″	30	199.0	15 9	21.2	30.7	31.3	24 8	.275

Tire Test Data (Continued)

Test No.	Car No.	Route	Type of Road	Speed M.P.H.	Total miles each test	Grams wear—each tire R.F.	L.F.	R.R.	L.R.	Grams Ave.	Wear per tire per 1000 miles
21	1	Colfax to	Concrete	30	400.4	22.7	11.4	24.4	21.5	20.0	.110
22	2	Steptoe	"	30	400.0	16.1	10.4	23.2	15.8	16.4	.090
23	1	"	"	30	399.0	15.9	14.5	25.4	21.2	19.2	.106
24	2	"	"	30	398.0	12.7	11.5	19.6	16.8	15.1	.084
31	1	Pendleton-	Oiled crushed	30	103.0	–4.0	–3.2	–2.6	–0.7	–2.6	—
32	2	The Dalles	rock macadam	30	103.0	–4.6	–1.4	–2.6	–1.5	–2.5	—
33	1	"	"	30	97.0	0.7	1.7	2.2	0.3	1.2	—
34	2	"	"	30	97.0	1.1	–0.7	3.0	–0.5	0.7	—
35	1	"	"	30	99.0	–1.5	–1.4	–1.8	–1.4	–1.5	—
36	2	"	"	30	99.0	0.5	–0.9	–4.3	–0.2	–1.2	—
37	1	"	"	30	203.0	3.9	1.1	5.0	1.4	2.8	.030
38	2	"	"	30	203.0	2.3	1.8	4.6	4.8	3.4	.037
39	1	"	"	30	400.0	4.5	0.0	1.0	5.2	2.7	.015
40	2	"	"	30	400.0	5.6	4.0	7.9	3.3	5.2	.028

only a normal amount of wear for this mileage. Throughout the tests there was no evidence of abnormal wear or of injury by accident to the casings. Each of the cars maintained perfect wheel alignment throughout the entire tests.

HUMIDITY

The success of the tests for tire wear depend in large measure upon the accuracy with which the tires can be weighed. It is a known fact that tires take up moisture very readily when exposed to air of higher humidity. This increase in weight of the tire due to absorbed moisture may sometimes equal the amount of rubber worn off in one or two hundred miles of travel. This fact makes it necessary to conduct the tests under conditions of uniform low humidity. For the summer of 1926, the relative humidity as determined from time to time during the tests ranged from 23 to 39% with an average of 31½%. Such a low humidity is especially conducive to accuracy in the results obtained and makes the region of Eastern Washington and Oregon especially adapted for tests of this nature.

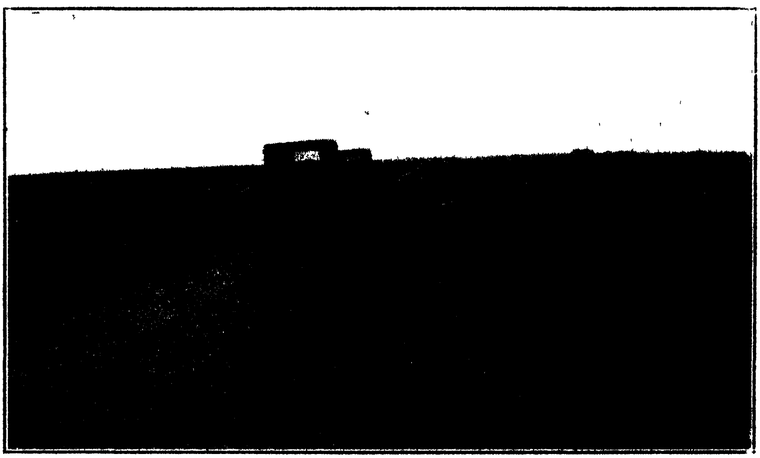

Figure 3. An example of the successful application of oil treatment to crushed basalt macadam highway near Pendleton, Oregon.

CONCLUSIONS

The results of the tests for the tire wear on crushed basalt macadam between Pullman and Palouse may be accepted as fairly representative of crushed rock highways which are in good condition. Likewise, the tire wear on the cement concrete pavement at Steptoe is representative of what may be expected on clean pavement.

In the case of the tests for tire wear on oil treated crushed rock macadam, a word of explanation is necessary. The test cars had been used on clean pavement and on dry gravel roads For each 100 miles of the first 300 miles traveled on the oil treated highway the tires apparently took up more weight of oil from the road surface than they lost in rubber worn off. Just how long this oil absorption would continue is not definitely known. However, the tests show that after the first 300 miles, the loss of weight by wear exceeded the gain in weight by absorption of oil. Continued tests did not reveal any apparent further absorption of oil as far as could be determined from the data secured. If it be conceded that the tires had become saturated with oil in the first 300 miles of operation on oil treated highways, then the subsequent tests show only the normal wear taking place on the oiled road surface. A study has been undertaken but no conclusions have been drawn as to the effect on the tread rubber of long continued use on oiled highways

The tests on oil treated highways were interrupted by rains which destroyed the low humidity conditions necessary for this type of work. Further tests will be carried out at the earliest opportunity.

On the basis of the results of the tests as shown in Fig. 4 economic conclusions may be drawn as follows:

If the average cost of tires in terms of pounds of tread rubber which is worn off the tire be taken as $10.00 per pound, a traffic of 500 cars per day on a good crushed rock highway will cost the motorists $2590 in tires per mile of highway per year. The cost on good cement concrete pavement would be $672 per mile and for oil treated surface in good condition $188 per mile per year.

The above figures on crushed basalt macadam are based upon the results derived from tests on 6683 miles of travel. The figures on

concrete pavement are based on 3431 miles of travel. This mileage is sufficient to establish the accuracy of the results pretty thoroughly. On the other hand, the results of the tests on oil treated highway are based on a total mileage of 1804 of which 600 miles were traveled before the tread wear exceeded the oil absorption. Therefore, the results of the tests on oil treated macadam are based practically upon but 1200 miles of travel and their probable accuracy should be considered accordingly.

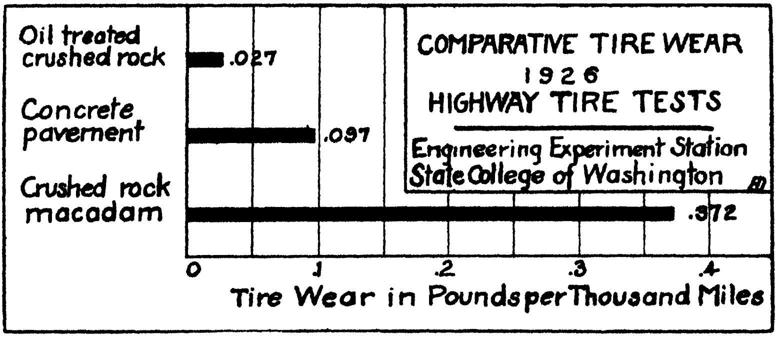

Figure 4

THE COST OF MOTORING OVER HILLS

What does a hill cost a motorist? It is quite generally agreed that a car will use more gasoline going up a hill than in going down the same hill. It would also seem reasonable to suppose that the tractive effort through the rear wheels to drive a car up hill would wear or grind off more tread rubber than in the process of going down hill. In the hope of determining these factors, tests were made on the Lewiston Hill in Idaho for gasoline consumption and tire wear going down hill as compared to traveling the same speed up hill. This route was chosen because of the fact that the grade is remarkably uniform and is comparatively long—two factors which are especially valuable in this kind of a test. The choice of this particular hill for hill tests is in no way a reflection upon the highway itself. The Lewiston Hill highway is a most excellent piece of engineering over a very difficult route, and affords the motorist a fine opportunity to view an expanse of rare Western scenery.

The Lewiston Hill Highway is approximately 8.5 miles long and has an elevation of 735 at the bottom and 2750 feet above sea level at the crest This gives an average grade for the entire hill of 4½%.

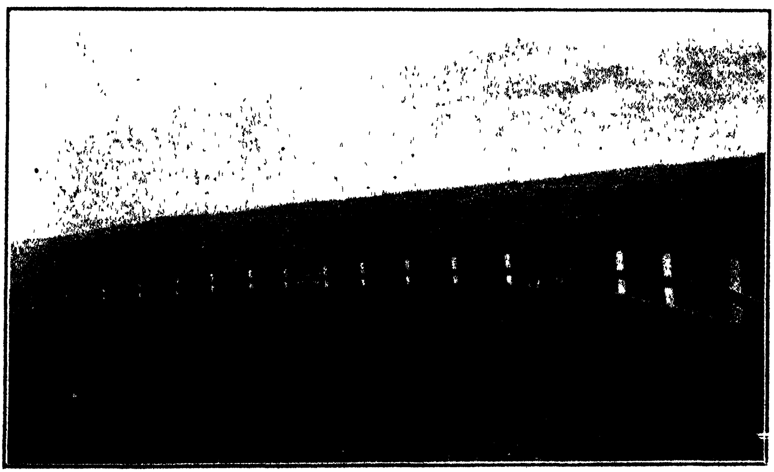

Figure 5. A well banked curve on the Lewiston Hill Highway. The loose crushed basalt on this type of highway undoubtedly contributes largely to the excessive tire wear experienced on Western macadam highways.

The maximum grade at any point does not exceed 5% while the minimum is 1½%. There are a number of sharp curves which are well banked. The entire highway on the hill is surfaced with loose crushed basalt which is frequently planed by a maintenance grader to keep it evenly distributed on the surface of the road.

METHOD OF HILL TESTS

TIRES

Two sets of tires and rims were used with one car. One set of tires was used on the trip down the hill, and at the bottom was replaced by the second set which was used on the return trip. The first set was then replaced and the performance repeated, keeping track, meanwhile, of the total miles each set of tires had traveled. Tires were always replaced on the same wheel, that is, one certain tire was always placed on the right rear wheel, while going down hill, etc. The speed was 20 miles per hour. Braking was done only when absolutely necessary and always as carefully as possible so that all skidding was avoided. Very little braking was necessary. The engine was always kept in gear with the ignition turned on while going down hill. Each set of tires when not in use was carried along in the test car. The tests were continued until each set of tires had run 50 miles. Then the tires were weighed and the two sets reversed—the "down hill" tires being used on the up hill trip and vice versa, for another 50 miles each. The results gave the tire wear for approximately 100 miles down hill and the tire wear for a like distance up hill. The usual thorough cleaning preceded the weighing before and after the tests.

GASOLINE

The test car was equipped with suitable valves in the gasoline line to the carburetor so that the rear tank supply could be used when going up hill, and on the down trip, gasoline could be drawn from a five gallon reserve tank attached to the dash of the car. In this way, all of the down hill mileage was made on gasoline weighed into the reserve tank, and the uphill mileage on gasoline weighed into the rear tank. Careful measurement was made of the quantities put in and of

the amount remaining after the test and computations made to determine the relative gasoline consumption for up hill, down hill ,and on the level.

CONCLUSIONS

Owing to the lack of time during the summer sufficient to carry out the entire tire test program which had been proposed, it was found impossible to complete the testing work on the Lewiston Hill highway. Furthermore, owing to an error made in the preparations for conducting this test, the accuracy of the data secured on the No. 1 set of tires was questioned, and therefore rejected. This leaves only the data on the No. 2 set of tires—representing a distance traveled during the test of 51.8 miles down hill and 43.4 miles up hill. This amount of data is entirely too meagre and the distance traveled is too short to justify drawing any conclusions as to the relative amount of wear to be expected in traveling up or down this type of highway. In Table 2 are submitted the results as obtained.

It is to be noted in Table 2 that the average wear up hill and down considerably exceeds the average wear experienced in travel on level highways.

Table 2

Route	Distance	Wear in lbs. per 1000 mi.
Down hill	51.8	.63
Up hill	43.4	1.01
Average	—	.82

Table 3

Route	Miles per Gal.	Gallons per 1000 miles
Level	18.6	53.8
Down hill	30.8	32.5
Up hill	11.6	86.4
Ave. uphill and down	16.8	59.4

An investigation was carried on at the same time relative to comparative gasoline consumption in the three cases noted. It will be observed that the average gasoline consumption up hill and down for a given distance is about 10% in excess of the consumption on average level highway.

Engineering Bulletins
Published by the Engineering Experiment Station
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1 Sewage Disposal for the Country Home.(Out of Print)
By O. L. Waller anod M. K. Snyder, Mar. 1914, July 1916

2 How to Measure Water.
By O. L. Waller. Oct. 1915. Reprint 1925.

3. Water Supply For the Country Home. (Out of Print.)
By M K. Snyder. See Eng'rg. Bul. No.'s 9 10 & 11).

4. Construction and Maintenance of Earth Roads..
By L. V. Edwards. April, 1916.

5. Cost of Pumping Water. (Reprinted as Extension Bul. No. 103.
By O. L. Waller. August, 1916.

6. Fuel Economy in Domestic Heating ond Cooking
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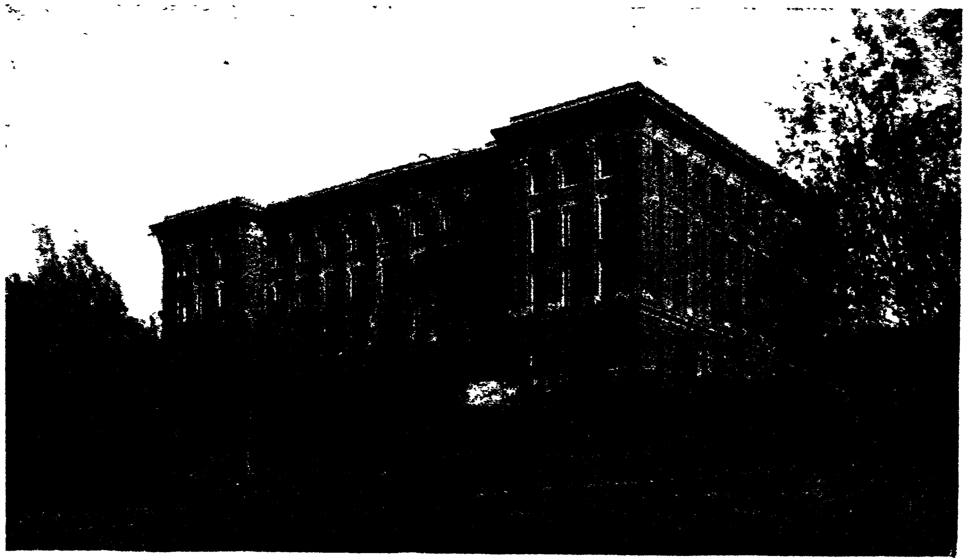
17. Relation of Road Surface to Automobile Tire Wear. Second Progrs Report. H. J. Dana. Dec. 1925.

18 Relation of Road Surface to Automobile Tire Wear. Third Progres Report. H. J. Dana. October. 1926.

19. Analysis of Washboards in Highways.
By H. V. Carpenter and H. J. Dana. (Nearly Completed).



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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 19 February, 1927 No. 9

Rhythmic Corrugations in Highways

by

H. V. Carpenter and H. J. Dana

ENGINEERING BULLETIN No. 19

ENGINEERING EXPERIMENT STATION

H. V. CARPENTER, Director

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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RHYTHMIC CORRUGATIONS IN HIGHWAYS

SUMMARY

The formation of rhythmic corrugations, or "washboards," in gravel and crushed rock highways has never been fully explained. Studies are here described, based first, on experiments carried out with an oscillographic recorder in the tonneau of a car which gives a record of the variation in distance between the rear axle and the body while going over "washboards" and various other obstructions. See Figures 1 to 9. These tests show that the rear axle frequently vibrates through vertical amplitudes many times greater than the depth of the corrugations. Second, to avoid the complicating vibrations found in practice a laboratory model of the rear end of an automobile was built which also eliminates horizontal motion. Then curves 9 to 15 were taken. These curves show the relationship in time between the rear axle and the road surface and show that at certain speeds the greatest pressure of the tire on the road comes in the trough of the corrugation. See Figure 12. The important effect of resonance is shown in Figure 9. Third, mathematical analyses based on the curves and the mechanics of the case explain many of the peculiar conditions found in these experiments.

INTRODUCTION

The rapid increase in the number of automobiles, with the consequent heavier traffic on the highways, has given rise to a peculiar and serious problem of highway maintenance. Many highways which are constructed with a gravel or crushed rock surface, especially those carrying a traffic of 500 or more cars per day, are subject to a form of erosion variously known as washboards, chatter bumps, rhythmic corrugations, etc. Much study has been devoted to the prevention or control of this undesirable formation by means of

improved construction, intensive maintenance, or special surface treatment but at present frequent planing is the most common treatment. This treatment is decidedly objectionable, not only from the standpoint of immediate expense but because the corrugations make it necessary to cut away a large amount of well compacted macadam. An acknowledged cure for washboards is pavement, but it is quite evident that all cases of washboards cannot be thus treated for many years to come and that gravel roads will continue to be subjected to abnormally heavy traffic. Therefore, it is important that effort be directed toward the elimination, or better control, of this nuisance.

The work of this bulletin has been directed toward a study and analysis of some of the causes contributing to the formation of washboards and to determine in what way they are inherent in the present design of the automobile itself.

OCCURRENCE OF WASHBOARDS

The formation of washboards is hindered by the maintenance of an abundance of sand or finely crushed rock on the road surface. They are found, occasionally, in the surface of bituminous macadam where the more or less soft surface material shapes itself into rhythmic undulations under the influence of traffic.

Where bituminous road surfaces break down by pitting, it is often noticed that the pits occur somewhat after the order of washboards, indicating that much the same force has been at work.

Cement concrete roads, and brick roads, do not reveal evidences of rhythmic corrugations due to traffic. If the surface in either case breaks down, it usually indicates destruction localized at that point because of a local weakness or injury in the surface

Earth roads usually do not show evidences of rhythmic corrugations. If the surface becomes rough under much traffic, it breaks down in irregular fashion, the pits and depressions usually showing no apparent regularity.

TIME OF APPEARING

Washboards in gravel and crushed rock highways appear mostly during dry seasons. The presence of moisture in the highway sur-

face tends to bind the surface particles together, making the formation of washboards less likely. This condition obtains in the spring of the year, but during a long dry summer, the surface moisture evaporates leaving the road material with a weaker binding agent, and therefore subject to rapid erosion through impact and air suction caused by passing tires.

RELATION OF VOLUME OF TRAFFIC TO FORMATION OF WASHBOARDS

A traffic of three or four hundred cars per day does not usually cause serious formation of washboards. By planing the crests of the bumps and re-distribution of loose gravel over the surface with a frequency proportioned to the traffic a much greater number of cars has been handled over gravel or crushed rock highways without serious corrugation. A temporary suspension of maintenance operations, of course, hastens the destruction of the road surface. Owing to the effect of other things than traffic volume upon the formation of washboards their formation cannot be ascribed to any arbitrary volume of traffic. It can be said, however, that the heavier the traffic, the more readily are washboards formed

Washboards have been found to occur on hills of a grade up to 5 and 6 per cent or steeper It has been asserted that they occur only on the side of ascending traffic but their occurrence has been occasionally noted also on the side of descending traffic. Such an example was observed on a hill at Nesqually Falls, Washington, in the summer of 1925, where a series of two or three hundred feet long of very prominent washboards occurred on the side of descending traffic On the side of ascending traffic no evidence of corrugation existed.

Observation has revealed the fact that corrugations do not ordinarily occur continuously over a long distance, but are formed in groups, which merge into one another. This is often indicated by the presence of a broken rhythm where one series has merged into another with a shortened cadence. The number counted in successive groups which have become joined together has ranged from nine to eighty-three each, while single independent groups seldom have more than 15 grooves per group.

CAUSE OF WASHBOARDS

Many theories have been advanced by various writers, as to the cause, and the method of formation of washboards. Some blame the explosions of the motor for the rhythm of the corrugations but this could not be true due to the fact that the road distance between explosions of the motor averages about 12 inches for four cylinder cars and from 6 to 10 inches for six cylinder cars, while the distance between corrugations as measured from crest to crest on the road surface where they occur has been found to range from 20 to 37 inches.

Modern demands for comfort in motoring have been met by providing highly perfected spring suspensions for the car bodies. The inertia of the body of the average automobile is large. The addition of passenger load further increases the inertia of the "sprung

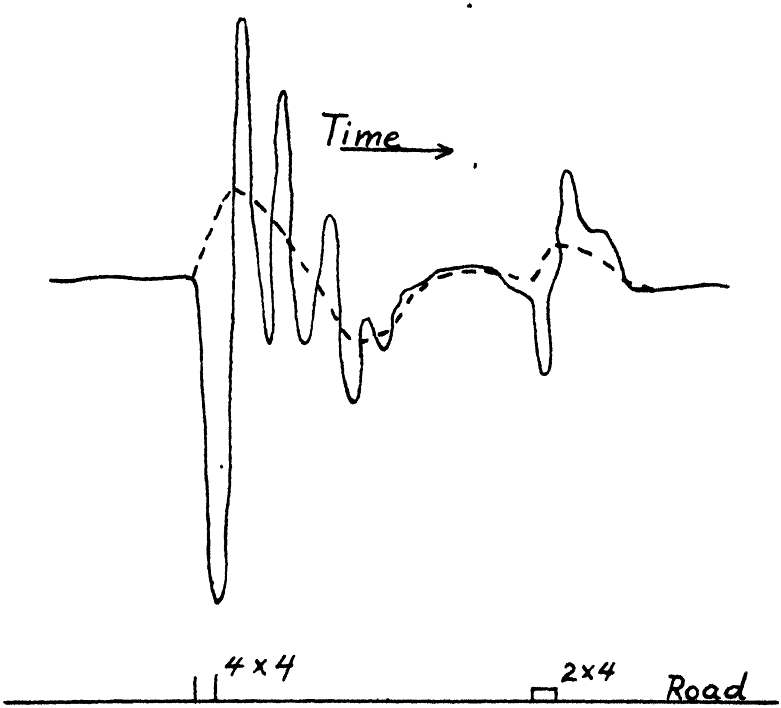

Fig. 1. Buick passing over bumps on a smooth road at 15 miles per hour. Dotted line shows apparent path of body.

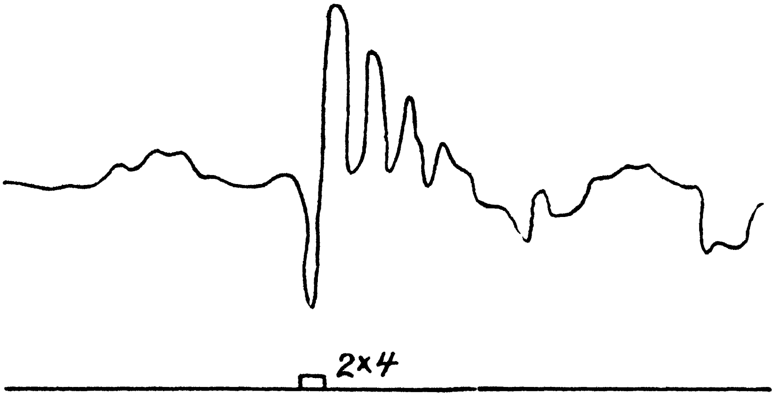

Fig. 2. Ford passing over a 2x4 at 20 miles per hour.

weight" of the car. This results in the desired protection against high frequency vibrations being transmitted to the passengers.

The wheels, tires and axle gear of the car constitute the "unsprung weight." This statement is only comparative, because of the fact that the tires, whether solid rubber, or pneumatic, constitute a "spring" for this so-called "unsprung weight," thus reducing to some degree the violence of the effect of road corrugations upon the axle.

The presence of very flexible springs between the car body and the axle makes it possible for the axle to vibrate almost independently of the body, a fact which is easily seen on the highway where the rear axle of the car being driven just ahead is frequently seen to be in violent oscillation while the body is vibrating only slightly.

In order to determine what relation might exist between axle vibration and road surface corrugations, three methods of investigation have been carried out: first, oscillographic recorder on a full sized car; second, a laboratory model car equipped with oscillographic recorder, and third, mathematical analysis.

First, a simple type of oscillographic recorder was built with a drum which revolves at a speed proportional to the speed of the car and was mounted in the tonneau. Upon the surface of this drum a pencil moves in proportion to the relative motion of the rear axle with respect to the car body. With this instrument in action the

car was driven over washboards and also over single bumps or depressions in an otherwise smooth road surface. These tests showed (see Figs. 1 to 5) that the natural frequency of vibration of the rear axle of a Ford Model T car is about 10.6 cycles per second when operating with standard tires and carrying 55 lbs. air pressure, and that the rear axle of a Buick Model 48 Victoria with cantilever

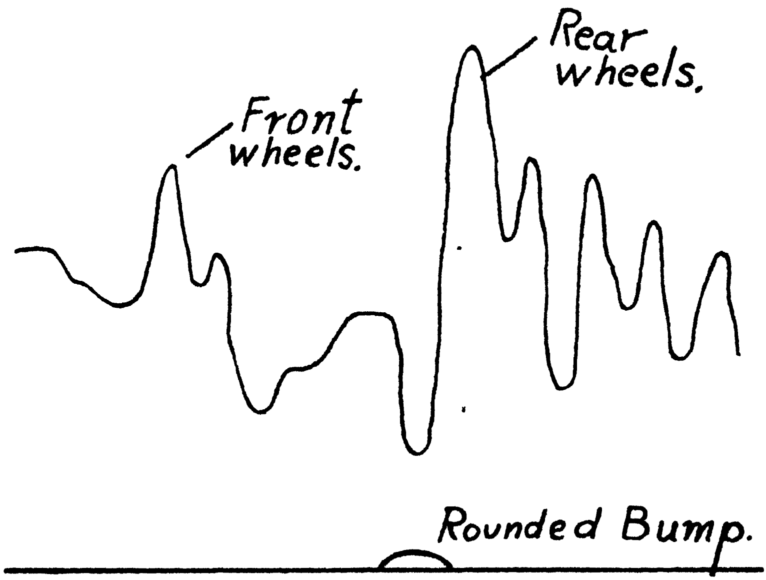

Fig. 3. Buick at 20 miles per hour.

springs and 5.77″ tires carrying 34 lbs. of air vibrates naturally 7.8 cycles per second. The difference is mainly in the weight of the axles. Measurements on many cases show that in western basaltic crushed rock roads the crests of the corrugations average 28.4″ apart. It follows that a Ford car axle would vibrate in resonance with the washboards when travelling over them at 17.1 miles per hour, or for the Buick, 12.7 miles per hour.

The records secured with the oscillograph while driving over washboards were quite irregular due to the many disturbing elements such as the effect of the front axle on the body, irregularities in the road surface, etc. Figures 6 and 7 show their character and bring

out two important points, first, that the rear axle oscillations are greater near the speed of resonance, second, that both show the vibration to be of the modulated wave type such as is used in radio telephony, indicating that the axle is vibrating with two frequencies at the same time, its own natural frequency and the frequency with which it is passing over the washboards. Figure 6 shows that the

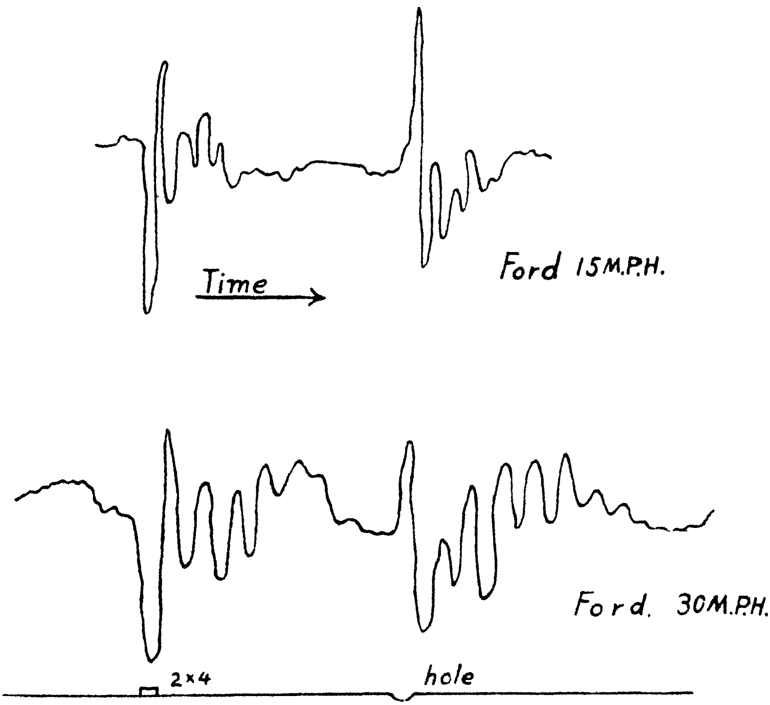

Fig. 4.

rear axle was vibrating through a range of about 3.8″ inches altho the corrugations were only about one inch in depth. This shows that it is quite possible for the tires to drop down into the troughs of the corrugations and jump over the crests, but the method used did not give any information on this point. It makes it seem likely that under the conditions of Fig. 6 at least the tires will exert their greatest pressure at a variety of points depending upon the relation

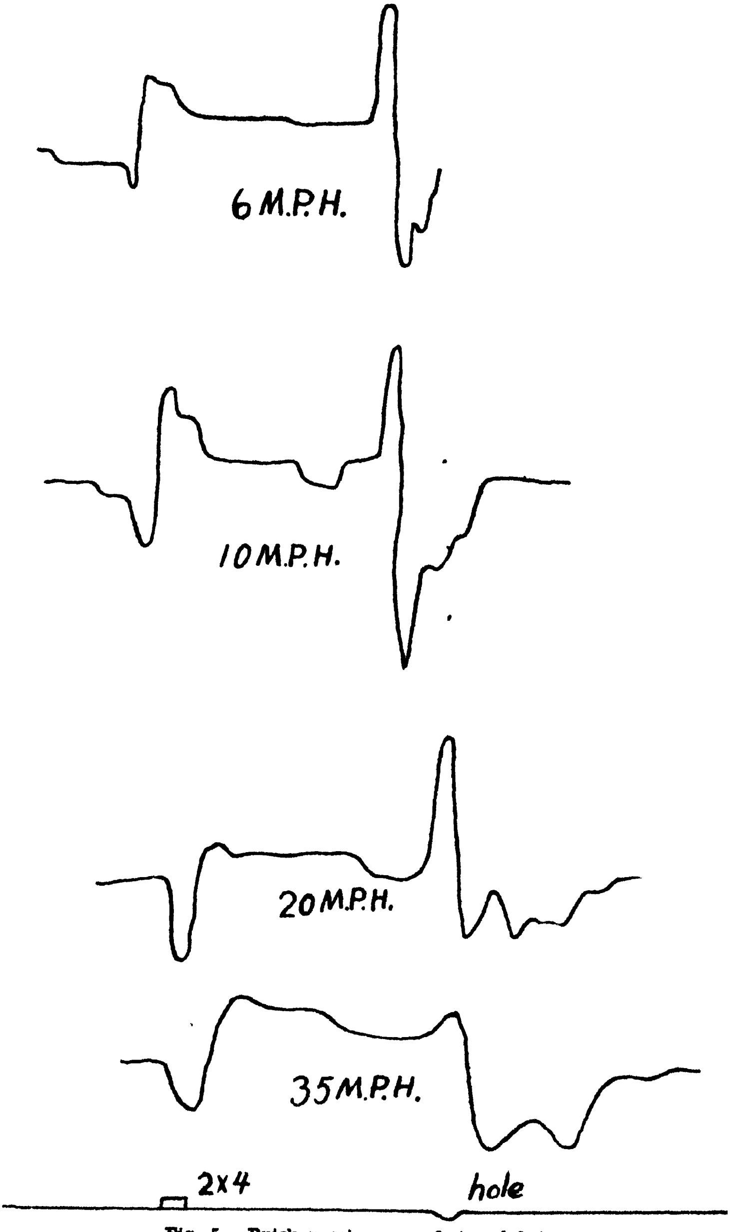

Fig. 5. Buick passing over 2x4 and hole.

of the phase of the natural oscillation to the phase of the impressed frequency coming from the road surface.

In order to bring out these relations more clearly the second method of studying the problem was developed in which a model was constructed using weights one-fiftieth as great as the actual weights of the loaded body of a Ford touring car as supported by the rear axle, (1100 lbs.) and the rear axle, wheels and tires, (200 lbs.). The "body" (wt. 22 lbs.) was connected to the "axle" (wt. = 4 lbs.) by a spring one two-hundredth as strong as the Ford springs (11.85 lbs. per ft. of stretch) and the tires were replaced by another spring

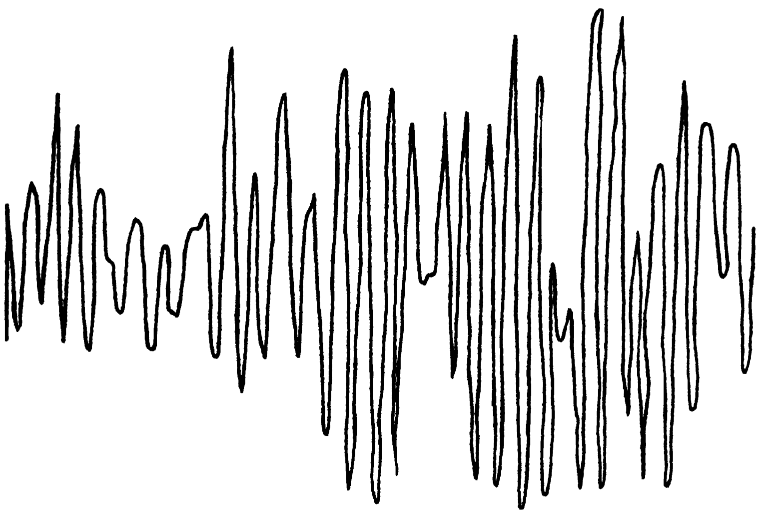

Fig. 6. Ford at 20 miles per hour over "washboards" ½" to 1" deep. Maximum motion of axle relative to body—3.82 inches.

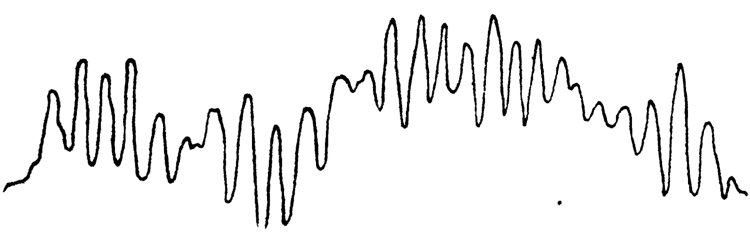

Fig. 7. Ford at 26 miles per hour over "washboards" ½" to 1" deep.

Fig. 8. Laboratory model.

in the same proportion (81 lbs per ft) connecting the "axle" with a reciprocating lever, (see Fig. 8). This lever can be driven by a motor at any speed and the throw can be adjusted to suit. The reci-

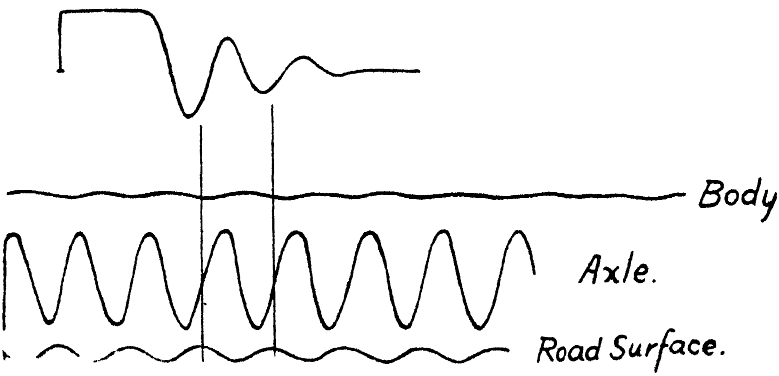

Fig. 9. Model of Ford rear axle at equivalent of 17.1 miles per hour. Note that axle vibration is about 8½ times the depth of the corrugations. The amount of friction in the springs is shown by the rate at which free oscillations of the axle die out—upper curve. Axle velocity about in phase with applied force.

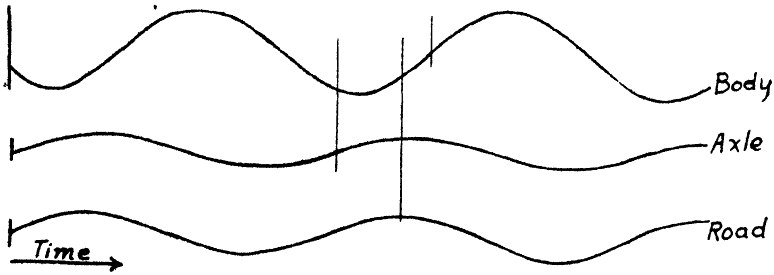

Fig. 10. Excessive body vibration at 2.2 miles per hour.

procating lever simulates the "washboards" and in operation the performance duplicates at one-half speed that of the rear end of a Ford except that all irregular disturbances from the road and disturbances caused by the front axle and by side sway, etc. are eliminated, and only the imitation of uniform corrugations remains.

Recording pencils were attached to the "body," "axle" and "road" respectively and records taken. See Appendix.

Fig. 9 shows the performance at 17.1 miles per hour, showing how this speed promotes excessive axle vibration. This is true because the frequency impressed on the tires by the road coincides with the natural frequency of the axle. Fig. 10 confirms the behavior of the axle in a startling manner by showing excessive vibration of the loaded body when the speed is about 2.2 miles per hour which

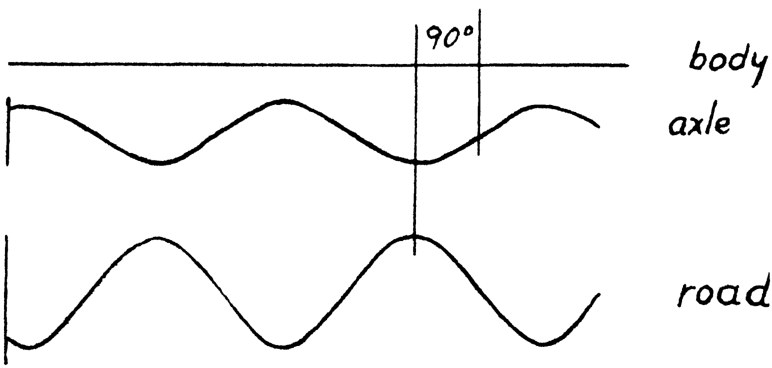

Fig. 11. Model at 30 miles per hour. Oscillation of axle about one half the depth of the corrugations.

makes the frequency of passing over corrugations approach the natural frequency of the body and springs. It should be noted in Figures 9 and 10 that the natural frequencies of the body and axle are so different that they do not respond greatly to each other.

Fig. 11 gives the record at an equivalent speed of 30 miles per hour showing that neither the body nor the axle is able to keep up with the corrugations and so do not vibrate greatly. This means that at high speeds the heaviest pressure of the tires must come at the crests of the corrugations although the tire surfaces will more nearly follow down into the troughs than these curves indicate through their tendency to smooth out the bumps by permitting the crest of the corrugations to sink more deeply into the tire. Many records at different speeds were taken bringing out the fact that at all speeds below the resonant speed for the axle the blow is struck by the tire as the axle swings down and comes into the trough of the corrugations. At resonant speed the blow is against the slope

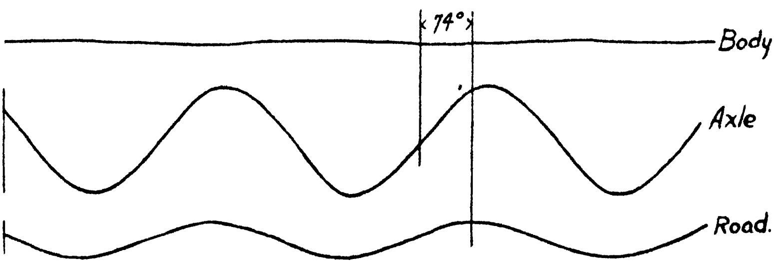

Fig. 12. Model at 14.9 miles per hour. Axle velocity leads applied force about 74°.

and at very high speeds is directly on the crest. This is shown by Figures 12, 9 and 13. This surprising shift of time relations together with other effects, is explained in the following theoretical analysis which is the third method of attacking the problem.

THEORETICAL ANALYSIS

It is the purpose in this analysis so to state the relations existing that the vibratory action of the axle can be determined by calculations based upon measurements of the deflection of the springs and tires per lb. of load, and the weights of axle and loaded body. This can

best be explained by beginning with the fundamental equations of oscillatory motion; and pointing out their adaptation to this problem.

The simplest type of mechanical vibration is that which occurs when a mass "m" is supported by a spring which tends to return the oscillating mass to its position of rest or equilibrium with a force which is proportional to the distance the mass is displaced from its position of rest. This results in simple harmonic motion: so-called

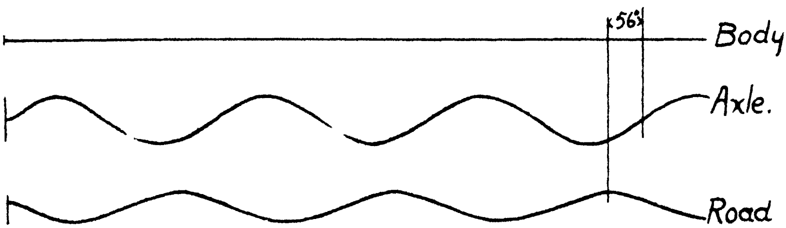

Fig. 13. Model at 20.7 miles per hour. Axle velocity lags behind applied force about 56°.

because it is the basis of all musical sound. (Harmonic motion is very common because most elastic bodies resist distortion with a force proportional to the distortion.) The equations expressing this relation of force to displacement may be derived as follows:

From experiment we know that:

$$F = ma \tag{1}$$

where "F" is force in poundals (= pounds force times "g" where "g" is 32.2), "m" is mass in pounds, and "a" is acceleration in feet per second per second.

Acceleration being the time-rate of change of velocity, it may be written

$$F = m \frac{d^2 y}{dt^2}$$

Where "y" is the displacement or distance of the mass from its position of rest.

Since, in the case under consideration, the force is proportional to the displacement "y" and in the opposite direction, we may write,

$$-m \frac{d^2y}{dt^2} = fy$$

where "f" is the restoring force in poundals of the spring **per foot of displacement of the mass,** or

$$m \frac{d^2y}{dt^2} + fy = 0 \qquad (2)$$

which is the common form of the differential equation of simple harmonic motion. Integration gives the more common formulae—

$$y = A \sin (p't + \Phi) \qquad (3)$$

where $p' = 2\pi/T$ where "T" is the time of a complete cycle of the motion. Also

$$T = 2\pi \sqrt{\frac{m}{f}} \qquad (4)$$

Both (3) and (4) are more commonly derived directly from the physical analysis of the motion of the pendulum, and the mechanics of circular motion.

Many conditions are found which enter in to complicate actual cases of oscillatory motion. These complicating causes may be divided into three classes. First, those which do not tend to add to or subtract from the energy of the oscillation. The most common of this class is the case where the spring does not offer a proportional resistance to displacement. This may be due to the shape or condition of use of the spring and is likely to lead to a motion which can be approximated by

$$m \frac{d^2y}{dt^2} + fy^r = 0$$

where "r" is an exponent which most nearly expresses the relation of force to displacement.

The effect of this deviation of spring resistance from the usual law of proportionality is to cause the motion of the body to deviate from the simple harmonic law by the introduction of smaller harmonics of higher frequency which will usually cause no apparent change in the performance, but which will lead to a change of wave form and cause the frequency of oscillations to depend somewhat upon the amplitude.

The second class includes all conditions whereby the oscillating body is caused to lose a portion of its energy of vibration at each point along its path. Prominent in this class of course is friction, which resists the motion of the body regardless of its direction. Imperfect elasticity of the springs is another. Friction may be found between the leaves of automobile springs in a very considerable amount, so that any vibrations set up will be quickly absorbed in spring friction. Shock absorbers or "snubbers" are commonly applied to increase this effect.

The motion which results when frictional or similar effects are added to an otherwise simple harmonic motion may best be expressed by adding a term to equation (2) above, which will express the usual condition that the vibration will be opposed, at each instant, by a force proportional to the speed of the vibrating body, or

$$m \frac{d^2y}{dt^2} + k \frac{dy}{dt} + fy = 0 \tag{5}$$

where "k" is the friction constant.

This formula may be stated in words as follows:—

The rate of decrease of velocity of an oscillating body as it swings away from its normal position until it comes to rest at the end of its swing is equal to a constant times its velocity because of frictional opposition, plus another constant times its displacement from normal position. The solution of this equation is found to be

$$y = Ae^{\frac{-kt}{2}} \sin Qt \tag{6}$$

where $Q^2 = p^2 - \frac{k^2}{4}$, p equals $2\pi f$ where f is the natural frequency with which the axle would vibrate without friction, and $e = 2.718$.

which is the formula for a damped oscillation. See Fig. 9 upper curve

This relation holds more closely true for cases where the friction is due to a viscious liquid, such as oil between automobile

springs, than in the case of friction between solids such as the leaves of dry automobile springs.*

In the third class of complicating conditions may be placed those cases wherein there is applied to the oscillating body a force which varies in cyclic fashion, and with a frequency of its own. This applied to a vibration which is otherwise simple harmonic gives a resulting motion which may be expressed as follows:

$$m \frac{d^2y}{dt^2} + fy = F \sin p\, t \tag{7}$$

where "F" measures the maximum value of the cyclic force, "p" indicates its frequency, and "t" is time in seconds. If the other complicating conditions discussed above are also present, the formula becomes:—

$$\ldots \frac{d^2y}{dt^2} + k \frac{dy}{dt} + fy^r = F \sin p\, t \tag{8}$$

The right hand member of (8) expresses only the frequency and force which the periodic force **tries** to cause the body to oscillate. If F sin p t is the only force present which tends to keep the body oscillating, the body will vibrate through $p/2\pi$ cycles per second but with an amplitude which depends not only on the strength of F sin p t but on the relation between its frequency and the natural frequency of the body when controlled by the springs alone. If, on the other hand, F sin p t is a less important force, and the body has energy of vibration from another source greater than that given it by F sin p t, then F sin p t only modulates the natural oscillation of the body. When $p' = p$ and F sin p t tends to act with the free oscillation, excessive vibration may result, as in any case of resonant or sympathetic response. See Figs. 6 and 9.

Any or all of these conditions may be present in the case of a car running over rhythmic corrugations with the added complication that we have two vibrating bodies, the axle and the body with its chassis and load, each with a different weight and a different force

* In this latter case the friction between dry leaves is likely to be roughly independent of velocity and proportional to the pressure between leaves. Since the car body and load are being supported the leaf pressure is much greater at one extreme of oscillation when the spring is compressed than at the other where the spring is relaxed. This leads to variations of wave shape within each cycle but the resultant effect is quite well expressed by formulae (5) and (6).

resisting displacement. The difficulty of analysis seems great but can be clarified as follows:

It is a matter of common experience that a car will pass over washboards at high speed with very little response on the part of the body to each individual bump from the road as shown by Figures 9 and 13. If we assume the car body to be unaffected we can consider the rear axle as being the body under analysis. This axle is subject to two spring controls, the car springs and the pneumatic tires; and it also has a cyclic force applied to it by the road corrugations acting through the tires.*

The axle is thus set into a forced complex harmonic oscillation of the type last described above, in which the natural period of the axle as determined by its weight and by the resistance to changes in compression of the springs plus the tires is combined with the independent cyclic force caused by the rhythmic corrugations passing under the tires.

In the ideal case where the speed of the car is assumed to be maintained constant over a uniform series of corrugations and the body is not vibrating, the only cause for oscillations of the axle is the corrugations. These will apply a cyclic force thru the tires to the axle and will build up in the axle a forced oscillation of the applied frequency and of an amplitude which is determined by the force applied, the weight of the axle, the strength of the springs, and the frictional opposition to oscillation which exists in the springs and tires. This is a form of harmonic motion which is expressed by formula (8) which becomes:—

$$m \frac{d^2y}{dt^2} + k \frac{dy}{dt} + fy = F \sin p t \qquad (9)$$

whenever the spring resistance is proportional to the deflection.

Assuming this to be the case it is desirable to determine, if possible, the relation which must exist between the motion of the

* The tires perform a very valuable function in smoothing out the effects of corrugations, just as they do for all other irregularities, by permitting the crest of a corrugation to sink into the tire deeper than the trough of a corrugation does. Thus a very slowly moving axle does not rise and fall by the full amount of the corrugation.

axle and the road corrugations, both as to amplitude of vibration and to phase relation.

Solution of (9) can be reached most clearly by steps. First, assume no friction and no restoring force due to springs. (9) becomes:

$$m \frac{dt^2}{d^2y} = F \sin p\, t \tag{10}$$

This closely approximates the condition at very high car speeds when the axle refuses to vibrate very much because of the high acceleration $\frac{d^2y}{dt^2}$ needed at the high frequency if the amplitude is also high. In other words the force F sin p t does not succeed in causing large vibration of the axle when p is large because the inertia of the heavy axle is such that the force cannot cause much acceleration and vibration is therefore limited.

Integrating equation (10) we have

$$m \frac{dy}{dt} = -\frac{1}{p} F \cos p\, t$$

or the velocity of the axle at any instant is

$$\frac{dy}{dt} = -\frac{1}{pm} F \cos p\, t \tag{11}$$

This shows that the maximum velocity which any force F sin p t can set up in the axle is inversely proportional to both p and m; and also that this velocity will be a maximum one quarter of a cycle after the force is a maximum in either direction. This is shown approximately by Figs. 11 and 13 which represent high speed conditions and shows the axle to be moving upward at its highest velocity nearly one quarter cycle after the application of maximum upward force. At this speed the inertia offers so much more opposition to vibration than the springs and the friction can offer that equation (11) is a fair approximation to the case.

Second, let it be assumed that the axle is so light that its inertia may be neglected and that there is no friction or shock absorber effect. Formula (9) becomes:

$$fy = F \sin p\,t \qquad (12)$$

This indicates that the maximum value of the displacement, y, comes at the instant when the force is a maximum, or, differentiating (12);

$$f\frac{dy}{dt} = p\,F \cos p\,t \qquad (13)$$

we find that the vibrating axle will have its maximum velocity in either direction one quarter cycle earlier than the maximum value of F sin p t is exerted in the same direction. This condition is approximated in Fig. 12 where the friction is made small and the speed is so slow that the inertia effect of the axle is small compared with the spring resistance

Third, in the same way assume that the frictional resistance to vibration is made so great that inertia and spring resistance may both be neglected. Then formula (9) becomes:

$$k\frac{dy}{dt} = F \sin p\,t \qquad (14)$$

which shows that the velocity is greatest when the force causing it is greatest This is shown in Fig. 14.

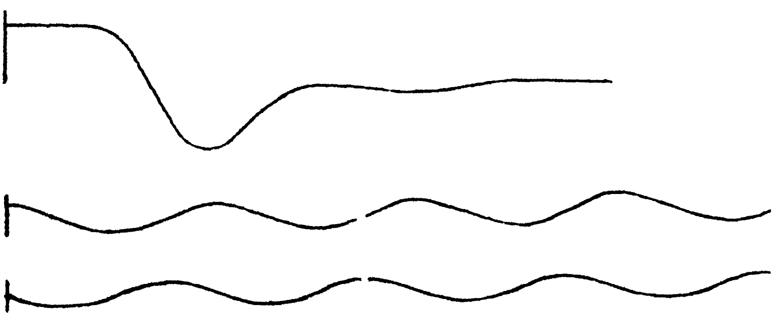

Fig. 14. Resonant speed with increased friction. See Fig. 9.

Now, if it be considered that the applied force is resisted by all three—inertia, friction, and springs—and assumed that the axle is vibrating in a definite phase and with a definite amplitude, use can be made of formulae (11), (13), and (14) to express the phase

and amount of the total applied force needed to cause the vibration assumed. Since the velocity of the axle, $\frac{dy}{dt}$, is common to all three,—

$$\frac{dy}{dt} = \frac{pf}{f} \cos p\ t = -\frac{1}{p\ m} F \cos p\ t = \frac{F}{k} \sin p\ t \qquad (15)$$

or, transposing and collecting the expressions for the force needed to overcome each component of opposition to the vibrating velocity,—

$$F \cos p\ t + F \sin p\ t = \left(\frac{f}{p} - p\ m\right) \frac{dy}{dt} + K \frac{dy}{dt} \qquad (16)$$

It is seen from (14) that the force to overcome friction is in phase with the velocity and therefore the expression V sin p t may be substituted for the expression $\frac{dy}{dt}$ since each expresses the velocity at the instant t, and it is known from (11), (13), and (14) that the velocity is a harmonic function. The second member may also be written in combined form so;

$$F \sin (p\ t \pm \phi) = \sqrt{\left(\frac{f}{p} - p\ m\right)^2 + k^2}\ V \sin p\ t \qquad (17)$$

where ϕ is the phase angle by which the applied force leads or lags behind the velocity V, and,

$$\phi = \tan \frac{\frac{f}{p} - p\ m}{k}$$

Formula (16) expresses fully the action of the axle when going at uniform speed over uniform corrugations provided further that the body of the car is not vibrating nor transmitting any disturbances from the front end These conditions apply in the laboratory model described above and the curves shown agree in every way with formula (17).

Examination of (17) and Figures 12, 9, and 13 show that at a certain speed only a small force will be required to cause a maximum velocity V in the axle, or, a given force will cause a high velocity or amplitude of vibration indicating that $\frac{f}{p} - p\ m$ equals

zero, while at either higher or lower speeds the vibration will be less.

Examination of equations (16) and (17) shows that as p changes the phase of V with respect to F sin p t will shift between the extremes indicated in formulae (11) and (13). This is shown also in the curves.

In analyzing the curves taken with the laboratory model the question first arises as to the relation between the to-and-fro movement of the lever which supplies the applied force and the actual road conditions. It is assumed in all cases, except one for very slow speeds, Fig. 10, that the car body moves only horizontally and the curves show this to be quite closely true. It will be admitted that if the body were permitted to move only horizontally while the car was moving so slowly that the inertia of the axle could be neglected, then the pressure of the road surface against the tires would be greatest with the tires on top of the crest of a corrugation. At higher speeds the same will be true except for the effects brought in by the combined action of the axle inertia and the spring action of the tires which tend to set up pressures of their own against the road. These latter reactions are fully accounted for in formulae (9) or (17); therefore, the applied force may be taken as being in phase with and proportional to the height of the road surface at the point of contact. This has been done throughout in the discussion of the curves.

Those who are familiar with the theory of alternating currents in electrical circuits will appreciate the complete analogy between the electrical circuit phenomena and the mechanical relations established above.

There are several additional points which must be considered. First, just when does the tire do the most cutting on the road surface? It seems probable that this happens during that part of the cycle when the tire is increasing its pressure, so that if it has started slipping and speeding up during the period of light contact it must slip under higher pressure until slowed down to normal speed. This would indicate cutting at speeds considerably higher than resonance.

Second, what happens when the tire leaves the ground at high speed? During this very short period the body may be considered to be free from vertical movement so that the axle would be free to

vibrate at a rate determined by the axle and car springs acting alone. This will be at a rate only about one third as fast as the frequencies shown, because of the weaker spring action. Therefore, when the tire is thrown clear of the road surface it will swing back more slowly and begin a series of skips from crest to crest over the corrugations. Its motion while doing this will be very complex, being made up of a part of a cycle of free swing followed by a much shorter interval in which it is controlled by both springs and tires. Since the contact surface of the road rises and falls beneath the tires, the tires and axle need not vibrate through any great amplitude during this skipping process. The tires are simply being struck a series of blows with so great rapidity that there is not time for the axle to vibrate through a large amplitude. It will be noted that the tire is not likely to lose contact with the road under these conditions unless the corrugations are deeper than the total depression made by the crest in the tire.

Third, what happens if the tire jumps off the road surface while going at resonant speed or below? Below resonant speed such a jump will slow down the natural period of the axle sufficiently to make its resultant vibration resonant and if it jumps too much it will be checked by falling out of step and will so adjust itself to this special resonant condition which, as the curves show, will tend to cause the heaviest road contact to take place in the troughs of the washboards. At resonant speed the tire will either be held to contact or will lose its stride and start over. The natural periods of the Ford and Buick cars used were found to be about 10.6 and 7.8 cycles per second respectively while the tires are in contact with the road and 3.8 and 3.24 cycles per second while the tires are in the air.

Figure 14 when compared with Figure 9 shows the effect of increased friction, indicating that snubbers or shock absorbers would tend to limit the violence of the axle vibration and so reduce the tendency to cut washboards. It seems quite probable that the added friction given by the various types of shock absorbers will not only protect passengers and springs but will reduce distructive tire wear due to excessive vibration of the axles and will reduce whatever tendency to cut washboards the axle may have at any speed, since the excessive vibrations are set up only after passing over several

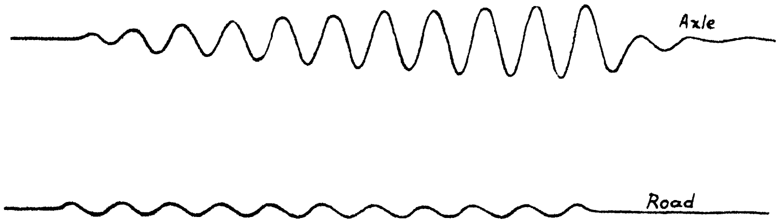

Fig. 15. Building up and dying out of axle vibration. 17.1 miles per hour.

corrugations (see Fig. 15) so that an efficient vibration absorbing device prevents vibration from building up. Thus it will be seen that the shock absorber serves a useful purpose for the axle and tires as well as adding to the comfort of the passengers.

The two cars mentioned are the only ones studied. However, one is quite typical of the light car class, having closely the same weight of axles as other cars approaching it in weight, while the Buick is typical of the heavier cars which run at higher average speed and are more likely to be equipped with shock absorbers.

The evidence indicates* that the light cars, driven usually at about their resonant speed are the guilty ones in cutting rhythmic corrugations as they are found at present.

Cars with softer tires, travelling at higher speeds and usually equipped with snubbers of some sort may throw a lot of gravel but are an asset rather than a liability so far as washboards are concerned.

The greater flexibility of the springs now coming into almost universal use tend to lower the speed at which the axles are resonant with the corrugations and so would seem to correct the trouble but there is no reason to think that the corrugations will not adjust themselves to new conditions and form with greater distances between crests If car design and car speed tend toward uniformity among the different makers the result will be an increase in the tendency to cut washboards at whatever spacing bests fits the average car at its average speed. Perhaps the increasing use of shock absorbers will more than offset this possibility.

It is proposed to continue this investigation in order to determine more definitely:—

First—The relative part played by front and rear axles in causing corrugations.

Second—The value of shock absorbers in reducing the tendency to form corrugations.

Third—The speed above which cars of various types do not cut corrugations.

Fourth—The relation of air pressure and tire size to the formation of corrugations.

Fifth—The relation of axle weight and total car weight to rate of cutting corrugations.

APPENDIX

Details of the Model Car Used

Fig. 8 shows the model as finally used. The "body" is a ball bearing car running with steel wheels on a smooth cast iron track so as to be practically frictionless. The "axle" is a mass with grooved races for rolling balls which roll upon the same track as the "body". The coil spring between "body" and "axle" is proportioned to represent the springs of the car while the spring connecting the "axle" with the vertical reciprocating lever is much stronger and is proportioned to act as the "tire". Stiff rods carry pencils which move across the paper record sheet shown. The record sheet is traversed by a separate motor seen in the background. The springs were made weaker by the ration of 4 to 1 than that required by direct proportionality in order that the vibratory action might take place at one half the frequency found in the actual car. (See formula 4.) This enables us to watch the performance to better advantage and determine better the adjustments needed in order to correctly reproduce the road conditions desired. Friction tending to limit the relative motion of the "body" and "axle" in order to simulate shock absorbers on the car was secured in the model by a simple adjustable sliding friction grip which was attached to the "axle" and gripped a rod extending from the 'body". It was found in adjusting this that if no friction was present the vibration set

up in the axle at resonant speed became to great too permit records being taken, even with the 'washboards" adjusted to a very slight "depth". On this account all records excepth Fig. 14 showing snubber action, were made with a close approximation to the normal spring action as shown by the way the vibrations die out in such cases, see Figs. 1 and 2. Damping curves are shown in Fig. 9 and 14. These were secured by setting the axle into free vibration by an outside force and taking a record with the "washboard" motor stationary. The "depth" of the "washboards" was adjusted by use of a crank of adjustable throw clamped in the key-way of the large "washboard" motor.

Many observers of this device questioned the equivalence of the model to the actual car because the weight of the "body" and "axle" were not borne by the "springs" and "tires" as in the actual car on the road. This apparent fault is seen to be absent when we remember that the springs and tires are compressed or extended the same amount by an additional force whether the weight is on them or not.

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol 9 March 1927 Number 10

How to Measure and Use Water for Irrigation

By O L WALLER

Second Revision

ENGINEERING BULLETIN No. 20

ENGINEERING EXPERIMENT STATION

H. V. CARPENTER, Director

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash, under Act of Aug 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Requests for copies of the engineering bulletins and inquiries for information on engineering and industrial problems should be addressed to The Engineering Experiment Station, State College of Washington, Pullman, Washington.

The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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INTRODUCTION

Inquiries come to this office for information concerning the measurement of water for irrigation. These queries are from farmers who are anxious to know whether they are getting the amount of water provided for in their contract.

The methods of measuring water are not familiar to them. Farmers are familiar with the process and know when they get true weights for their stock and produce, but the measurement of running water introduces an element of time that gives trouble.

To assist such people and to make it possible for them to know that they are getting what is due them, the following pages have been written

No attempt has been made to develop or explain formulae. Technical terms have generally been avoided and common language used. For the scientist, plenty has been written, and the effort now should be to put this knowledge into a working form for those who have daily use for it.

Most contracts in this state provide for the delivery of water from April 1st to Nov. 1st, a period of seven months, or 210 days. The average growing season, during which time water is needed for crop production, is about four months or 120 days. Consequently, if the water-user gets all the water his contract calls for he should get 1¾ as much as he contracts for continuously during the 120 day period. If not used continuously during that period, then a further increase should be made. If his contract provides for one cubic foot per second for 160 acres, continuous flow, service to begin April 1st and close Nov. 1st, his land would receive 32 acre-inches of water, or the equivalent of 32 inches of rainfall.

If it were used continuously for 120 days only, the land would receive 18¼ acre-inches. As the number of days during which water is used are reduced, the amount used should be proportionally increased. In many instances the amount of water provided for in the

contract is in excess of the demands of the crop. The irrigator has a right to all the water he can beneficially use, but not to more than is agreed to in his contract. This bulletin in no way undertakes to discuss the water needs of the various crops; neither does it offer any suggestions as to how to irrigate, or to till the ground so as to conserve the moisture. It gives information only as to how to measure water. Experience has shown that plants need most water during June, July and August; that a continuous flow is not needed, is not economical, and under good practice is not generally used; consequently, the farmer's supply ditches and measuring weirs should be ample in size to carry a large head of water for short periods, so that the water not needed in April, May, September and October may be used during the hot months

Since our statute does not recognize the miner's inch as a unit of measurement in the distribution of water, and since there is no standard miner's inch in use in this state, no definitition will be attempted

HOW TO MEASURE WATER

THE "SECOND FOOT"

The state law of Washington provides that in appropriating water to ditches the quantity shall be estimated in cubic feet per second. The cubic foot per second and decimals thereof not only provide a legal unit of measure, but one that is uniform the world over and should, therefore, be understood by everyone. It is an absolute unit whose quantity cannot be subject to dispute

Since the opening through a miner's inch measuring box is liable to be clogged by floating weeds and other debris, and since it therefore frequently fails to deliver the full rated quantity, and thereby entails a loss upon the water user, it is generally considered better practice to use a weir for measuring water because it is very much less liable to be choked by debris floating in the canal

To determine the quantity of water flowing in a stream, it is necessary to measure the amount of water passing a definite point each second of time and multiply that quantity by the number of seconds it is flowing. One cubic foot per second, as is usually provided by contract in this state, means 7½ gallons or one cubic foot for every second of time Contracts for water for irrigation usually call for the water to be delivered from April 1st to November 1st

Instead of scales to weigh the quantity of water that passes a given point in a stream each second of time, or of a gallon measure to measure it with a weir is used, which accurately measures the amount of water that flows over it each second of time

We may imagine a trough, flume or ditch leading away from a river, creek, or lake, and a man dipping water from the stream or lake with a bucket holding 7½ gallons and pouring it into the ditch or flume. If he dips up one bucketful every second and pours it into his canal or flume the stream flowing away to his irrigated field will be one cubic foot per second or one "second-foot," as it is

sometimes called. Such a stream of water would cover two acres of land 12 inches deep every 24 hours. In other words, one "second-foot" will cover one acre one inch deep every hour or one acre 24 inches deep in 24 hours. One cubic foot of water per second, running for one hour will deliver enough water to cover one acre one inch deep. Three thousand, six hundred cubic feet of water or 27,000 gallons, will cover one acre approximately one inch deep.

To speak of a "second-foot" (one cubic foot per second), without specifying the time or duration of the flow, gives no definite information as to the total quantity of water supplied.

THE "ACRE-FOOT"

It is often convenient in irrigation to describe a certain volume of stored water. Since the "second-foot" can be used only for running water the "acre-foot" has been quite generally adopted for the measure of stored water. This unit represents the quantity of water required to cover one acre one foot deep. Since there are 43,560 square feet in an acre, there are 43,560 cubic feet of water in one acre-foot. The acre-foot is a unit of volume, and does not carry the time element with it.

The most accurate and convenient method of measuring small streams is by means of weirs. Both rectangular and trapezoidal or Cippoletti weirs are in use. The U. S. Department of Agriculture generally uses the Cippoletti weir and, on account of its wide use among irrigators, this form of weir will be described and tables inserted to determine the discharge.

If the conditions set forth in the following pages are complied with, the worst results should not contain more that one or two per cent of error.

Mr. Ryan in Bulletin 6, of the Montana Experiment Station, says, "No device for measuring flowing water has been more thoroughly tested and experimented with than the weir, with the result that, notwithstanding the simplicity of its construction, we may, by taking proper precautions, determine the amount of water flowing over it within one per cent."

To secure accurate measurements the following rules should be observed, both in selecting the size of the weir and in placing the same.

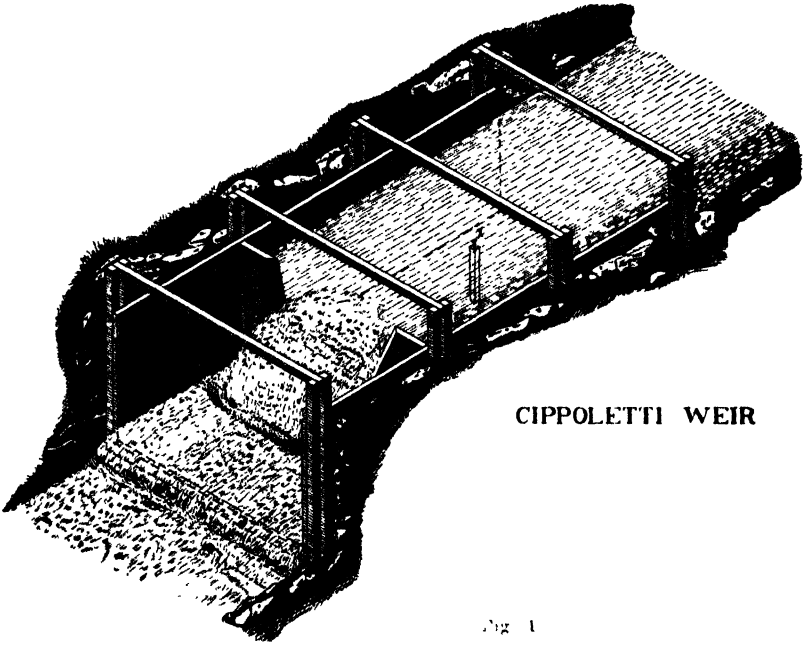


Fig. 1

Figures 1, 2, and 3 show a trapezoidal or Cippoletti weir, the sides having a inclination of one horizontal to four vertical. Figure 2 shows the notch in detail. The line B C is called the crest of the weir. The slope of the sides, A B and C D, is one inch horizontal for every four vertical. B C is the length of the weir. In a one-foot weir B C is 12 inches long. Figure 3 shows the post from the top of which the depth of the water over the crest of the weir is to be measured.

HOW TO INSTALL MEASURING WEIRS

It is believed that the sketches show the details of construction with sufficient clearness to permit of the proper placing of both the weir and the post from which the depths are to be measured. (See Fig. 3).

The dimensions of the flume in which the weir is placed will be governed by the volume of water to be measured, but in no case should the length of the flume be less than 8 feet nor the width be less than the width on the surface water line of the ditch. The bottom of the flume should be level in both directions. Its upstream end should be placed on grade with the bottom of the ditch so that

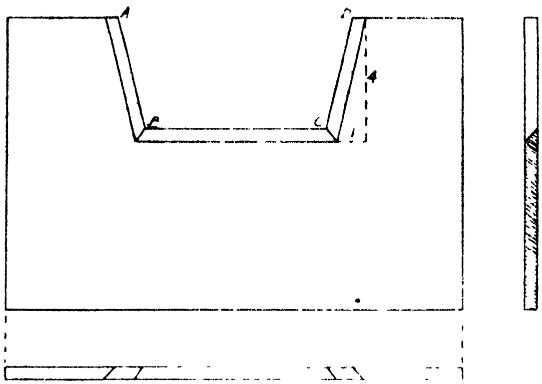


Fig 2

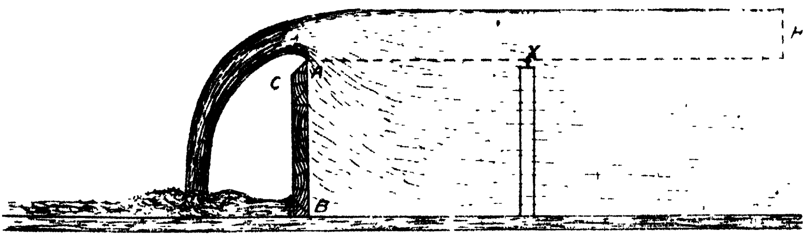


Fig 3

water will enter without eddies or disturbances. The channel of the ditch should have a uniform grade and cross section for 100 feet upstream from the flume, if possible, and its axis should pass through and parallel to the middle of the structure.

The end and bottom contractions of the stream pouring over the weir must be complete. To secure this: (a) The opening in the weir must be in a plane surface perpendicular to the course of the water; (b) the upstream edge must be beveled to a sharp crest; (c) the distance of the crest of the weir from the bottom of the flume

must be three times the maximum depth of the water intended to pass over the weir; (d) the distance from the ends of the crest of the weir to sides of the flume should be not less than twice the maximum depth of water to flow over the weir.

The greatest depth of water allowable on the crest of the weir should be not more than one-third, or better, one-fourth the length of the crest of the weir, and the depth should be not less than three inches. Where these conditions are not met, it would be better to use a longer weir where the depth of water flowing over the crest is more than one third the length of the weir or a shorter one where the flow over the weir is less than three inches.

The measuring post can be nailed either to the bottom or the sides of the flume and should be placed three or four feet back of the weir board. Into the top of said post drive a nail, the head of which is exactly level with the crest of the weir. In the Cippoletti weir it will be noticed that the opening or notch is of regular trapezoidal form; that is, the top and bottom are horizontal and the sides slope at an angle of one inch horizontal to four inches vertical.

In constructing a weir to measure a given amount of water, the first thing is to determine the length of its crest. Suppose one second-foot is allowed by contract for each 160 acres of land, and the farmer has 40 acres to be watered, then he has the right to 0.25 second-feet if there is to be a continuous flow of water. If, however, it is to be delivered in good big working heads as suggested in an other part of this bulletin, then the crest should be 1½ to 2 feet long.

The notch is chamfered and placed with a sharp edge on the up stream side and is usually backed up by steel or galvanized iron so as to offer a sharp edge for the water to pass over. This may be done by tacking a strip of No. 20 or 22 gauge galvanized iron to the upstream, or vertical face of the weir. Said strip should be placed along the crest and sides of the weir. Care should be taken to so place these strips that the opening through which the water flows is left the proper size, and that the water in passing touches nothing but the sharp edge of the metal.

The weir-board may be slid in between a pair of guides while measurements are made, and it may then be removed. This is an

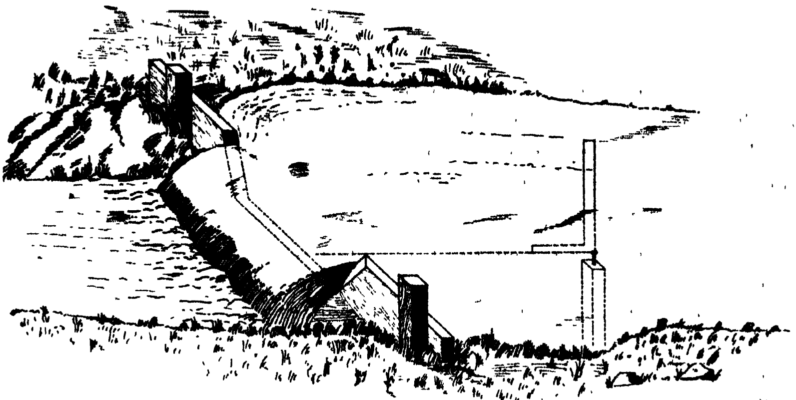


Fig. 4

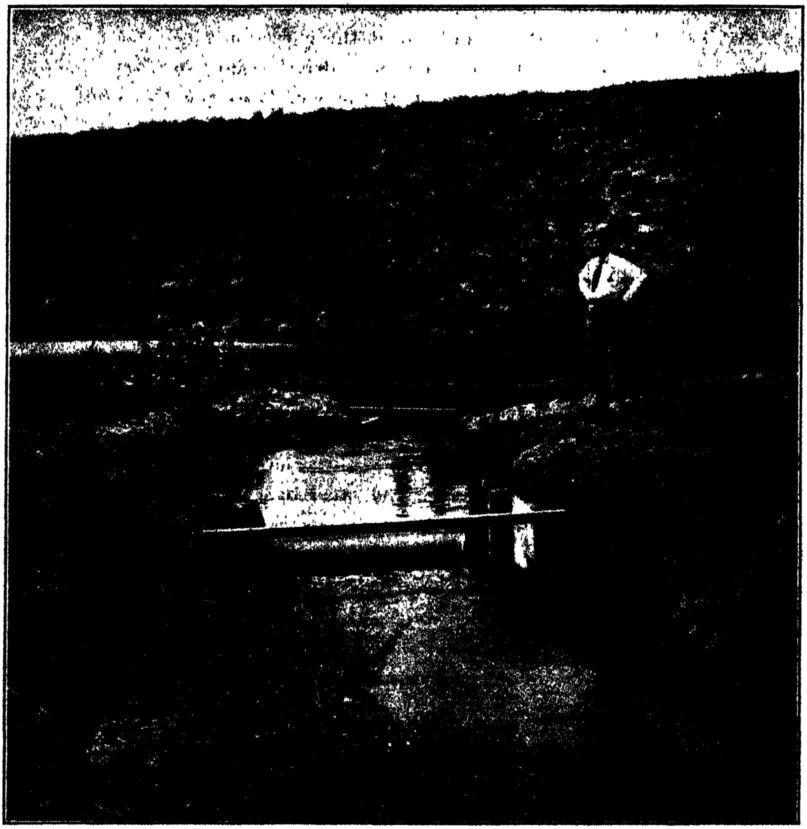


Fig. 5

excellent plan when there is rubbish, weeds, mud, etc., in the water. By such an arrangement the flume is kept clean and the measurements will be correct. Where a measuring box is filled with mud and rubbish up even with the crest of the weir, the discharge is in excess of what it should be and the measurement can not be relied upon.

Sometimes it will be possible by damming up the stream to so widen and deepen its section that a weir can be set without the expense of a flume. (See Fig. 4). This can only be recommended where a temporary measurement is wanted. When such a plan is adopted, the weir should be placed at right angles to the current of the stream at a point where the channel is straight for some distance above the weir, and the current, if any be noticed, should head into the center of the overflow space. The water should be brought as nearly as possible to a state of rest above the weir by artifically widening and deepening the stream. In general the rules governing the placing of a weir in a flume should be observed in placing a weir in a stream where the flume is not used.

The intent of the rules for construction and placing of a weir is to provide that the cross section of the water in the flume or channel back of the weir shall be seven to eight times that of the cross section of the water over the crest of the weir, and that the velocity of the stream as it approaches the weir shall not be more than one-half foot per second. When these conditions obtain, the measurements will be satisfactory.

The accompanying illustrations (Figs 4 and 5) will assist the beginner in placing a weir in a stream where the flume is omitted In such instances an apron, or paved floor, should be provided to receive the falling water, otherwise the dam and weir would likely wash out.

LOCATION OF WEIR

A measuring weir should be placed on the farm lateral 50 feet or more, if possible, below the head-gate which diverts the water from the canal. The head-gate should be set to let as much water flow over the weir as is desired and should then be locked.

HOW TO MEASURE WATER OVER A WEIR

After the weir has been set and a little time has been allowed for the water to reach its highest level, take any common ruler or carpenter's square graduated to inches and eighths, and, holding it plumb, measure the depth of water from the top of the nail in the measuring post or block, as the case may be. This measurement is never made on the weir-board, but always on the peg or block, set a considerable distance back from the weir board, as explained elsewhere.

Suppose the depth is found to be four and one-eighth inches, the observer should then follow down the first column in the weir tables until 4⅛ inches is reached, then follow that line across the page to the column representing the length of the weir and read the discharge in cubic feet per second. If an 18-inch weir has been used he should then follow down column one to 4⅛ inches and across the page to column headed 1½ foot weir and read the discharge 1.00 cubic foot per second.

If it is desired to measure the amount of water in a stream, before building a weir to measure the water, it will be necessary to make an approximate estimate of the amount flowing in the stream and of the grade of the stream. Suppose it was estimated that the stream was flowing 12 cubic feet per second, and the grade was such as to permit the placing of a 7½ foot weir. Then on page 21 under column headed "7½ feet," follow down to 12.03, thence to the left to column two which will show a depth of 7⅜ inches. A weir of this length will, with reasonable accuracy, measure one-fourth to six times the amount estimated, thus allowing for stream fluctuation. A longer weir might be used, but the depth over the crest would hardly be sufficient for the best measurement.

If an irrigator wanted a full head of water with which to irrigate 10 acres, he should have about two second-feet with which the whole ten acres could be watered in about twenty hours. For such a quantity of water the crest of the weir should be two feet long and the depth over it about 5⅜ inches. On page two of the table, following down the column headed inches, to 5⅜, then to the right to the column showing the length of the weir crest to be 2 feet, the observer will find 2.03 second-feet for the discharge.

On pages 7 and 8 the cubic foot per second and the acre foot are defined. From said definitions it will be seen that the quantities in Table I doubled will give approximate acre feet per 24 hours. Table II, however, showing cubic feet per second and equivalent acre feet per 24 hours for short length weirs, such as are generally used by farmers, has been introduced for the convenience of water-users. The irrigator, when watering, wants to know how much water he is putting on his land and the table in acre feet will be found most convenient for that purpose. If the farmer has made a study of his soil and the plant requirements for water, he will be able to put the right amount of water on the land.

Example: Suppose 2¼ second feet are turned out at a head-gate, how many acres could be watered 4 inches deep in 24 hours? This would be water enough to cover one acre 54 inches deep, or 13½ acres 4 inches deep, in 24 hours.

WORKING HEAD

To get the most out of water and to apply it most economically, the farmer should have as large a working head as one man can look after, say 1 to 2 "second-feet" or more, depending upon the ground, the skill of the irrigator, and the methods of irrigation.

For South Idaho, Wayman recommends one to one and one-fourth second-feet. Walsh puts the top limit at 2 second-feet. Bliss says 2 second-feet for flooding and says irrigators must learn to use larger working heads under the rotation system and thus increase the efficiency of the water supply. Jessup says 1½ to 2 second-feet is the size of an average irrigation head in Colorado. Savage says it is a demonstrated and accepted fact that each irrigator should be given the largest head of water he can economically handle and **retain it on his land.** Sanford says two second-feet is about the limit. He further says the delivery of water by rotation is the most practical and economical method, both from the viewpoint of the canal operator and the water-user.

If 4 acre-inches per acre be applied to average ground at each watering, it will wet the ground about 30 inches deep and put it in good growing condition. A working head of 2 second-feet would

therefore irrigate 40 acres in about 80 hours, or 160 acres in approximately 13⅓ days. If water, therefore, were distributed by rotation on a 7½ day interval, large farms would require more than one man to attend to the irrigating.

PROPORTIONED ACCORDING TO TIME

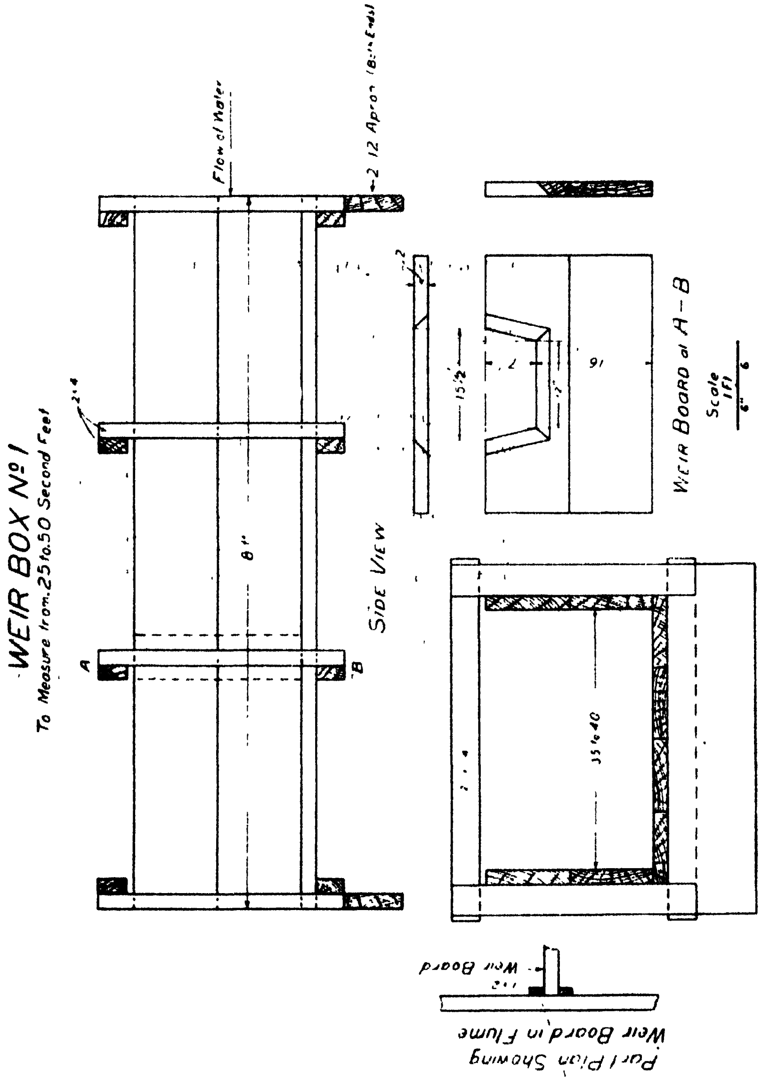
The ordinary way of delivering a small stream of water continuously not only wastes the water, but squanders the time of the irrigator; while it over-saturates the ground near the head ditches and leaves the crop to "burn" farthest away. With a large head or supply of water, all one man can conveniently distribute, the ground is quickly and evenly wet, and the farmer may then go about other duties, a very important one of which is the cultivation of the irrigated ground as soon as the surface is sufficiently dried.

An arrangement between the farmers and the ditch companies providing for the distribution of water by rotation, so that each one would have a good working head when he wanted to irrigate, would be a great economy both to the farmers and to the ditch companies, and incidentally make the water now available serve a much larger acreage.

ACKNOWLEDGMENTS

Cuts and estimates for weir boxes were prepared by Samuel Fortier, chief of irrigation investigations, U. S. Department of Agriculture.

Table II was computed by Dr. Elmer C. Colpitts.

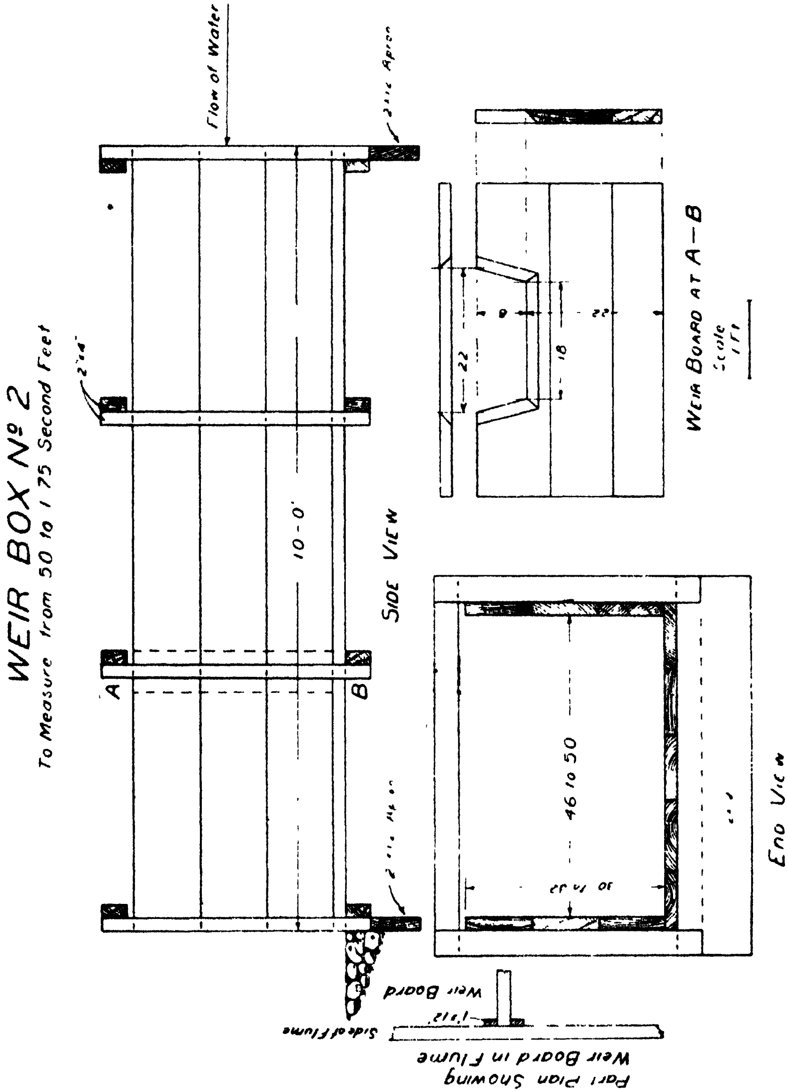

WEIR BOX No 1
To Measure from .25 to .50 Second Feet
Flow of Water
2 12 Apron (Both Ends)
2x4
A
B
8'
Side View
15½
12"
16
Weir Board at A—B
Scale
35 to 40
End View
Weir Board
Part Plan Showing
Weir Board in Flume

BILL OF MATERIAL FOR WEIR BOX NO. 1

No. of pieces	Actual Dimensions In. In. Ft In.	Feet B. M.	Where Used	Remarks
4	2x12x8	64	Lining, Sides	Lumber, Rough
3	2x12x8	48	Lining, Sides	Lumber, Rough
1	2x10x8	13½	Lining, Bottom	Lumber, Rough
8	2x 4x4 2	22⅓	Sills and Ties	Lumber, Rough
8	2x 4x2 10	15	Posts	Lumber, Rough
2	2x12x4 2	16⅔	Aprons	Lumber, Rough
2	2x12x3 1½	12½	Weir board	Clear Lumber Surfaced
4	1x 2x3	1¼	Cleats, Sides	Clear Lumber Surfaced
2	1x 2x3	1	Cleats, Bottom	Clear Lumber Surfaced

7 lbs. 20d. nails.

½lb. 6d nails.


WEIR BOX No 2
To Measure from 50 to 175 Second Feet
Flow of Water
A
B
10-0'
Side View
22
18
8
Weir Board at A—B
46 to 50
End View
Weir Board
Side of Flume
Part Plan Showing
Weir Board in Flume

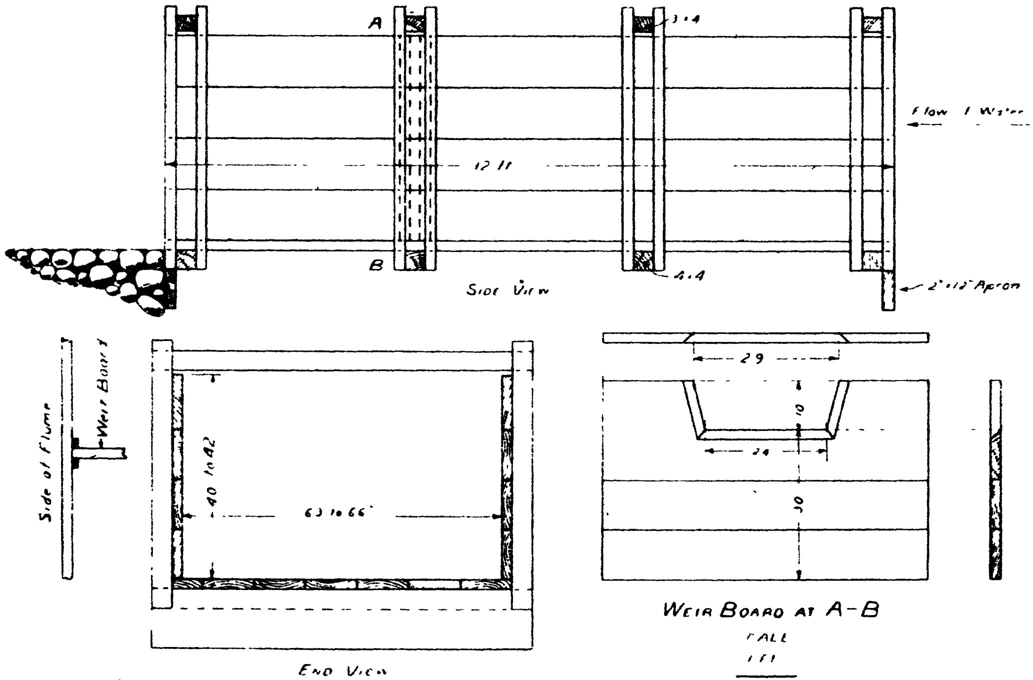
BILL OF MATERIAL FOR WEIR BOX NO. 2

No of Pieces	Actual Dimensions	B. M. Feet	Where Used	Remarks
	In. In. Ft. In.			
6	2x12x10	120	Lining, Sides	Lumber, Rough
4	2x12x10	80	Lining, Bottom	Lumber, Rough
1	2x 6x10	10	Lining, Bottom	Lumber, Rough
8	2x 4x 5	26⅔	Sills and Ties	Lumber, Rough
8	1x 2x 2 6	17¾	Posts	Lumber, Rough
2	2x12x 5	20	Aprons	Lumber, Rough
2	2x12x 4	16	Weir Board	Clear Lumber Surfaced
1	2x10x 4	6⅔	Weir Board	Clear Lumber Surfaced
4	2x 4x 3 4	1⅔	Cleats, Sides	Clear Lumber Surfaced
2	1x 2x 4	1⅓	Cleats, Bottom	Clear Lumber Surfaced

7½ lbs. 20d. wire nails.
½lb. 6d. wire nails.

WEIR BOX No 3

To Measure from 75 to 3 5 Second Feet



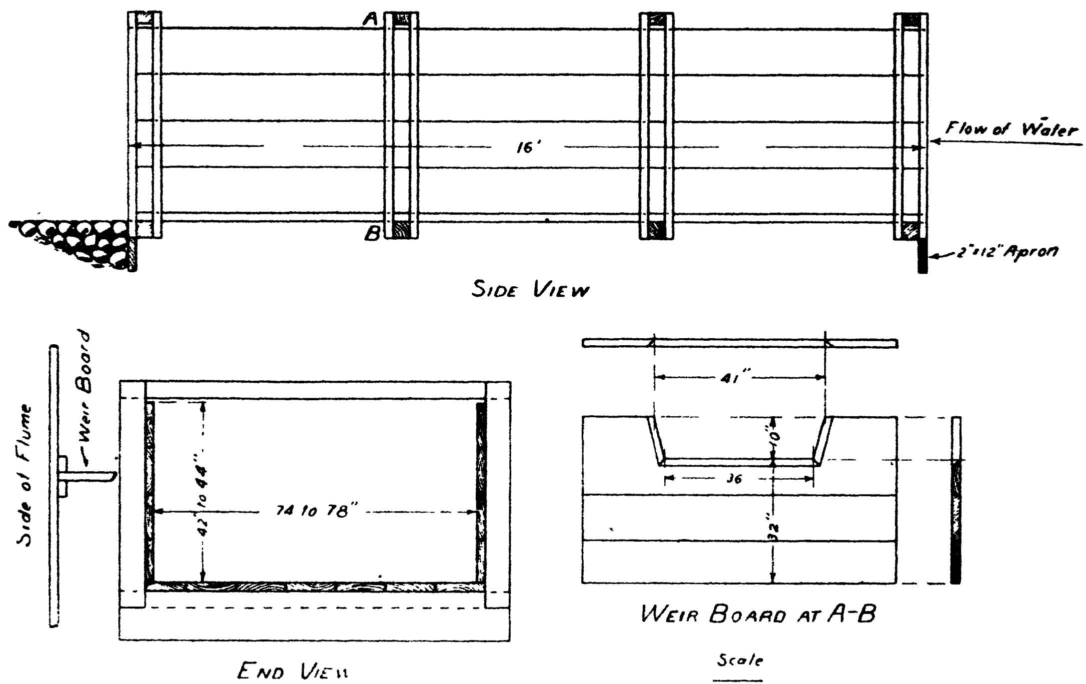
BILL OF MATERIAL FOR WEIR BOX NO. 3

No. of Pieces	Actual Dimensions	B. M. Feet	Where Used	Remarks
	In. In. Ft. In.			
6	2x12x12	144	Lining, Sides	Lumber, Rough
2	2x10x12	40	Lining, Sides	Lumber, Rough
3	2x12x12	72	Lining, Bottom	Lumber, Rough
4	2x10x12	80	Lining, Bottom	Lumber, Rough
4	4x 4x 6 4	34	Sills	Lumber, Rough
4	3x 4x 6 4	24	Ties	Lumber, Rough
16	2x 4x 4 2	67	Posts	Lumber, Rough
2	2x12x 6 4	25⅓	Aprons	Lumber, Rough
1	2x18x 5 4½	16	Weir Board	Clear Lumber Surfaced
2	2x12x 5 4¼	21½	Weir Board	Clear Lumber Surfaced
4	1x 2x 3 4	2¼	Cleats on Sides	Clear Lumber Surfaced
2	1x 2x 5 4½	1½	Cleats, Bottom	Clear Lumber Surfaced

11 lbs. 20d. wire nails.
½lb. 6d. wire nails.

WEIR BOX No. 4

To Measure from 1. to 10 Second Feet



BILL OF MATERIAL FOR WEIR BOX NO. 4

No. of Pieces	Actual Dimensions In. In Ft In	Feet B. M.	Where Used	Remarks
6	2x12x16	190	Lining, Sides	Lumber, Rough
2	2x10x16	53⅓	Lining, Sides	Lumber, Rough
4	2x12x16	128	Lining, Bottom	Lumber, Rough
4	2x10x16	106⅔	Lining, Bottom	Lumber, Rough
4	4x 4x 7 8	40 8/9	Sills	Lumber, Rough
4	3x 4x 7 8	30⅔	Ties	Lumber, Rough
16	2x 6x 4 4	69⅓	Posts	Lumber, Rough
2	2x12x 7 8	30⅔	Aprons	Lumber, Rough
1	2x16x 6 4	16 8/9	Weir Board	Clear Lumber Surfaced
2	2x14x 6 4	29 5/9	Weir Board	Clear Lumber Surfaced
4	1x 2x 2 6	1⅔	Cleats on Sides	Clear Lumber Surfaced
2	1x 2x 6 4	2 1/9	Cleats, Bottom	Clear Lumber Surfaced

12 lbs. 20d. wire nails.

1 lb. 6d. wire nails.

TABLE NUMBER I

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR

For Various Lengths and Depths Formula: Q equals 3.367 LH 3-2

Head "H" on crest Measured in Still Water		Discharge in Cubic Feet per Second											
		Length of Weir Crest in Feet											
Feet	Inches Approx	1	1½	2	2½	3	3½	4	5	7½	10	12½	15
.01	⅛	.003	.01	01	.01	.01	01	01	.02	02	03	04	.05
.02	¼	010	.01	.02	.02	.03	03	.04	.05	.07	10	12	.14
.03	⅜	.018	.03	04	.04	.05	.06	07	.09	.13	18	.22	.26
04	½	.027	.04	.06	.07	.08	.09	11	.13	.20	.27	.34	.40
05	⅝	038	.06	.08	09	11	13	15	.19	28	.38	47	.56
06	¾	.050	.07	.10	.12	.15	17	20	.25	37	.49	.62	.74
.07	⅞	.062	09	12	.16	.19	.22	.25	.31	.47	.62	.78	94
08	1	076	.11	.15	.19	.23	27	.30	.38	57	.76	95	1.14
09	⅛	.091	14	18	23	27	.32	.36	45	68	.91	1.14	1 36
10	¼	107	.16	.21	.27	32	.37	.43	53	80	1 06	1 33	1 60
11	1 ⅜	.123	.18	25	.31	.37	.43	.49	61	92	1 23	1.54	1.84
12	½	140	.21	.28	35	.42	49	.56	.70	1 05	1.40	1.75	2.10
13	9-16	.158	24	.32	.39	47	55	.63	79	1 18	1.58	1.97	2.37
14	⅝	176	26	.35	.44	53	.62	.71	.88	1 32	1 76	2 20	2 65
15	¾	196	.29	39	.49	59	.68	78	98	1.47	1 96	2.44	2 93
16	1 ⅞	.216	32	43	54	65	75	86	1 08	1.62	2 15	2.69	3 23
17	2	236	35	47	.59	71	83	.94	1 18	1 77	2.36	2.95	3.54
18	⅛	257	.39	51	64	.77	90	1.03	1 29	1 93	2.57	3.21	3.86
19	¼	279	.42	56	70	84	98	1.12	1 39	2 09	2.79	3 49	4 18
20	⅜	301	45	60	75	90	1 05	1 20	1.51	2.26	3 01	3 76	4 52
21	2 ½	324	49	65	81	.97	1 13	1.30	1.62	2 43	3 24	4 05	4.86
22	⅝	347	.52	69	87	1 04	1.22	1 39	1.74	2.61	3.47	4 34	5 21
23	¾	371	.56	.74	93	1.11	1 30	1.49	1 86	2 79	3.71	4 64	5.57
24	⅞	.396	.59	79	99	1 19	1 39	1 58	1 98	2 97	3 96	4.95	5 94
25	3	421	63	84	1 05	1 26	1 47	1 68	2 10	3 16	4 21	5 26	6.31
26	3 ⅛	446	67	89	1 12	1 34	1 56	1 79	2 23	3 35	4.46	5.58	6 70
.27	¼	472	71	94	1 18	1 42	1 65	1.89	2.36	3 54	4 72	5 90	7.09
28	⅜	499	75	1 00	1 25	1 50	1.75	2.00	2.49	3 74	4 99	6.24	7.48
29	½	526	79	1 05	1.31	1.58	1 84	2.10	2 63	3 94	5.26	6 57	7 89
30	⅝	553	83	1 11	1 38	1.66	1 94	2 21	2 77	4.15	5.53	6 92	8 30
.31	3 ¾	.	87	1 16	1 45	1 74	2.03	2 32	2 91	4 36	5 81	7 26	8.72
32	⅞		91	1 22	1 52	1 83	2 13	2 44	3 05	4.57	6 09	7 62	9.11
33	4		.96	1 28	1.60	1 91	2 23	2 55	3 19	4 79	6.38	7 98	9 57
34	⅛	. .	1 00	1 33	1.67	2 00	2 34	2.67	3 34	5 01	6 67	8 34	10 0
35	¼		1 0[illegible]	1 39	1 74	2 09	2.44	2 79	3.49	5 23	6 97	8 71	10 4
36	4 ⅜	. .	1 09	1 45	1.82	2.18	2 56	2.91	3.64	5.45	7.27	9 09	10.9
37	½		1.14	1.52	1 89	2.27	2 65	3.03	3.79	5.68	7.58	9 47	11 3
.38	9-16	. . .	1 18	1.58	1.97	2.37	2.76	3.15	3.94	5 91	7.89	9.86	11.8
39	⅝	. .	1 23	1 64	2.05	2 46	2 87	3 28	4.10	6.15	8 20	10.2	12.3
40	¾	.	1 28	1 70	2 13	2 56	2 98	3.41	4.26	6 39	8.52	10 6	12.7
41	4 ⅞	.	1.33	1 77	2.21	2.65	3.09	3 54	4.42	6.63	8 84	11.0	13.2
.42	5	. .	1 37	1.83	2.29	2.75	3.21	3.67	4 58	6.87	9.16	11.4	13.7
.43	⅛	.	1.42	1 90	2 37	2 85	3 32	3 80	4 75	7.12	9.49	11 8	14.2
.44	¼	.	1.47	1 97	2.46	2 95	3.44	3.93	4 91	7 37	9.83	12.2	14.7
45	⅜	.	1 52	2.03	2.55	3.05	3 56	4.07	5.08	7.62	10 1	12 7	15.2
46	5 ½	. . .	1.58	2.10	2.63	3.15	3.68	4.20	5.25	7.88	10 5	13.1	15.7
.47	⅝	. . .	1.63	2.17	2.71	3.25	3.80	4.34	5.42	8.14	10.8	13.5	16.2
.48	¾	. . . .	1.68	2.24	2.80	3.36	3.92	4.48	5.60	8.40	11 2	14.0	16 7
.49	⅞	. . . .	1 73	2.31	2.89	3.46	4.04	4.62	5.77	8.66	11.5	14.4	17.3
.50	6	. . . .	1 79	2.38	2.98	3.57	4.17	4.76	5.95	8.93	11.9	14.8	17 8

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR—Continued

For Various Lengths and Depths Formula: Q equals 3.367 LH 3-2

Head "H" on crest Measured in Still Water		Discharge in Cubic Feet per Second											
		Length of Weir Crest in Feet											
Feet	Inches Approx.	1½	2	2½	3	3½	4	5	7½	10	12½	15	18
.51	6⅛	1.84	2.45	3.07	3.68	4.29	4.90	6.13	9.20	12.2	15.3	18.3	22.0
.52	¼	1.89	2.52	3.16	3.79	4.42	5.05	6.31	9.47	12.6	15.7	18.9	22.7
.53	⅜	1.95	2.60	3.25	3.90	4.55	5.20	6.50	9.74	12.9	16.2	19.4	23.3
.54	½	2.00	2.67	3.34	4.01	4.68	5.34	6.68	10.0	13.3	16.7	20.0	24.0
.55	⅝	2.06	2.75	3.43	4.12	4.81	5.49	6.87	10.3	13.7	17.1	20.6	24.7
56	6¾	2.12	2.82	3.53	4.23	4.94	5.64	7.05	10.5	14.1	17.6	21.1	25.4
.57	⅞	2.17	2.90	3.62	4.35	5.07	5.80	7.24	10.8	14.4	18.1	21.7	26.0
.58	7	2.23	2.97	3.72	4.46	5.20	5.95	7.44	11.1	14.8	18.5	22.3	26.7
59	⅛	2.29	3.05	3.81	4.58	5.34	6.10	7.63	11.4	15.2	19.0	22.8	27.4
.60	¼	2.35	3.13	3.91	4.69	5.48	6.26	7.82	11.7	15.6	19.5	23.4	28.1
.61	7⅜	....	3.21	4.01	4.81	5.61	6.42	8.02	12.0	16.0	20.0	24.0	28.8
.62	½	....	3.29	4.11	4.93	5.75	6.57	8.22	12.3	16.4	20.5	24.6	29.5
.63	9-16	....	3.37	4.21	5 05	5.89	6.73	8.42	12.6	16.8	21.0	25.2	30.3
64	⅝	....	3.45	4.31	5.17	6.03	6.89	8.62	12.9	17.2	21.5	25.8	31.0
.65	¾	....	3.53	4.41	5.29	6.18	7.06	8.82	13.2	17.6	22.0	26.4	31.7
.66	7⅞	....	3.61	4.51	5.42	6.32	7.22	9.03	13.5	18.0	22.5	27.0	32.4
.67	8	....	3.69	4.62	5 54	6.46	7.39	9.23	13.8	18.4	23 0	27.7	33.2
.68	⅛	....	3.78	4.72	5.66	6.61	7.55	9.44	14.1	18.8	23.6	28.3	33 9
69	¼	....	3.86	4.82	5.79	6.75	7.72	9.65	14.4	19.3	24.1	28.9	34.7
.70	⅜	....	3.94	4.93	5.92	6.90	7.89	9.86	14.7	19.7	24.6	29.5	35.4
.71	8½	....	4.03	5.04	6.04	7.05	8.06	10.0	15 1	20.1	25.1	30.2	36.2
.72	⅝	....	4.11	5.14	6.17	7.20	8.23	10.2	15.4	20.5	25.7	30.8	37.0
.73	¾	....	4.20	5.25	6.30	7.35	8.40	10.5	15.7	21.0	26.2	31.5	37.8
.74	⅞	....	4.29	5.36	6.43	7.50	8.57	10.7	16.0	21.4	26.7	32.1	38.5
.75	9	....	4.37	5.47	6.56	7.65	8.75	10.9	16.4	21.8	27.3	32.8	39.3
76	9⅛	....	4.46	5.58	6.69	7.81	8.92	11.1	16.7	22.3	27.8	33.4	40.1
.77	¼	....	4.55	5.69	6.82	7.96	9.10	11.3	17.0	22.7	28.4	34.1	40.9
.78	⅜	....	4.64	5.80	6.96	8.12	9.28	11.6	17.3	23.1	28.9	34.7	41.7
.79	½	....	4.73	5.91	7 09	8.27	9.46	11.8	17 7	23.6	29.5	35.4	42.5
80	⅝	....	4.82	6.02	7.23	8.43	9.64	12.0	18.0	24.0	30.1	36.1	43.3
.81	9¾	....	4.91	6.14	7.36	8.59	9.82	12.2	18.4	24.5	30.6	36.8	44.1
.82	⅞	....	5.00	6.25	7.50	8.75	10.0	12.5	18.7	25.0	31.2	37.5	45.0
.83	10	....	5.09	6.36	7.64	8.91	10.1	12.7	19.0	25.4	31.8	38.1	45.8
.84	⅛	....	5.18	6.48	7.78	9.07	10.3	12.9	19.4	25.9	32.4	38.8	46.6
.85	¼	....	5.28	6.60	7.92	9.23	10.5	13.1	19.7	26.3	32.9	39.5	47.4
86	10⅜	....	5.37	6.71	8.06	9.40	10.7	13.4	20.1	26.8	33.5	40.2	48.3
.87	½	....	5.46	6.83	8.20	9.56	10.9	13.6	20.4	27.3	34.1	40.9	49.1
.88	9-16	....	5.56	6.95	8.34	9.73	11.1	13.9	20.8	27.7	34.7	41.6	50.0
.89	⅝	....	5.65	7.07	8.48	9.89	11.3	14.1	21.2	28.2	35.3	42.4	50.8
.90	¾	....	5.75	7.19	8.62	10.0	11.5	14.3	21.5	28.7	35.9	43.1	51.7
.91	10⅞	....	....	7.31	8.77	10.2	11.6	14.6	21.9	29.2	36.5	43.8	52.6
.92	11	....	....	7.43	8.91	10.4	11.8	14.8	22.2	29.7	37.1	44.5	53.4
.93	⅛	....	....	7.55	9.06	10.5	12.0	15.1	22.6	30.1	37.7	45.2	54.3
.94	¼	....	....	7.67	9.20	10.7	12.2	15.3	23.0	30.6	38.3	46.0	55.2
.95	⅜	....	....	7.79	9.35	10.9	12.4	15.5	23.3	31.1	38.9	46.7	56.1
.96	11½	....	....	7.92	9.50	11.0	12.6	15.8	23.7	31.6	39.5	47.5	57.0
.97	⅝	....	....	8.04	9.65	11.2	12.8	16.0	24.1	32.1	40.2	48.2	57.8
98	¾	....	....	8.17	9.80	11.4	13.0	16.3	24.4	32.6	40.8	48.9	58.7
.99	⅞	....	....	8.29	9.95	11.6	13.2	16.5	24.8	33.1	41.4	49.7	59.6
1.00	12	....	....	8.42	10.1	11.7	13.4	16.8	25.2	33 6	42 0	50.5	60.6

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR—Continued

For Various Lengths and Depths Formula: Q equals 3.367 LH 3-2

Head "H" on crest Measured in Still Water: Feet	Inches Approx	Discharge in Cubic Feet per Second — Length of Weir Crest in Feet: 2½	3	3½	4	5	7½		12½	15	18	20
1.01	12⅛	8.54	10.2	11.9	13.6	17.0	25.6	34.1	42.7	51.2	61.5	68.3
1.02	¼	8.67	10.4	12.1	13.8	17.3	26.0	34.6	43.3	52.0	62.4	69.3
1.03	⅜	8.80	10.5	12.3	14.0	17.6	26.3	35.1	43.9	52.7	63.3	70.3
1.04	½	8.93	10.7	12.5	14.2	17.8	26.7	35.7	44.6	53.5	64.2	71.4
1.05	⅝	9.06	10.8	12.6	14.4	18.1	27.1	36.2	45.2	54.3	65.2	72.4
1.06	12¾	9.19	11.0	12.8	14.7	18.3	27.5	36.7	45.9	55.1	66.1	73.4
1.07	⅞	9.32	11.1	13.0	14.9	18.6	27.9	37.2	46.5	55.8	67.0	74.5
1.08	13	9.45	11.3	13.2	15.1	18.8	28.3	37.7	47.2	56.6	68.0	75.5
1.09	⅛	9.58	11.4	13.4	15.3	19.1	28.7	38.3	47.8	57.4	68.9	76.6
1.10	¼	9.71	11.6	13.5	15.5	19.4	29.1	38.8	48.5	58.2	69.9	77.6
1.11	13⅜	9.84	11.8	13.7	15.7	19.6	29.5	39.3	49.2	59.0	70.8	78.7
1.12	½	9.98	11.9	13.9	15.9	19.9	29.9	39.9	49.8	59.8	71.8	79.8
1.13	9-16	10.1	12.1	14.1	15.1	20.2	30.3	40.4	50.5	60.6	72.7	80.8
1.14	⅝	10.2	12.2	14.3	16.3	20.4	30.7	40.9	51.2	61.4	73.7	81.9
1.15	¾	10.3	12.4	14.5	16.6	20.7	31.1	41.5	51.9	62.2	74.7	83.0
1.16	13⅞	10.5	12.6	14.7	16.8	21.0	31.5	42.0	52.5	63.0	75.7	84.1
1.17	14	10.6	12.7	14.9	17.0	21.3	31.9	42.6	53.2	63.9	76.6	85.2
1.18	⅛	10.7	12.9	15.1	17.2	21.5	32.3	43.1	53.9	64.7	77.6	86.3
1.19	¼	10.9	13.1	15.3	17.4	21.8	32.7	43.7	54.6	65.5	78.6	87.4
1.20	⅜	11.0	13.2	15.4	17.7	22.1	33.1	44.2	55.3	66.3	79.6	88.5
1.21	14½		13.4	15.6	17.9	22.4	33.6	44.8	56.0	67.2	80.6	89.6
1.22	⅝		13.6	15.8	18.1	22.6	34.0	45.3	56.7	68.0	81.6	90.7
1.23	¾		13.7	16.0	18.3	22.9	34.4	45.9	57.4	68.8	82.6	91.8
1.24	⅞		13.9	16.2	18.5	23.2	34.8	46.4	58.1	69.7	83.6	92.9
1.25	15		14.1	16.4	18.8	23.5	35.2	47.0	58.8	70.5	84.6	94.1
1.26	15⅛		14.2	16.6	19.0	23.8	35.7	47.6	59.5	71.4	85.7	95.2
1.27	¼		14.4	16.8	19.2	24.0	36.1	48.1	60.2	72.2	86.7	96.3
1.28	⅜		14.6	17.0	19.5	24.3	36.5	48.7	60.9	73.1	87.7	97.5
1.29	½		14.8	17.2	19.7	24.6	37.0	49.3	61.6	73.9	88.7	98.6
1.30	⅝		14.9	17.4	19.9	24.9	37.4	49.9	62.3	74.8	89.8	99.8
1.31	15¾		15.1	17.6	20.1	25.2	37.8	50.4	63.1	75.7	90.8	100
1.32	⅞		15.3	17.8	20.4	25.5	38.2	51.0	63.8	76.5	91.9	102
1.33	16		15.4	18.0	20.6	25.8	38.7	51.6	64.5	77.4	92.9	103
1.34	⅛		15.6	18.2	20.8	26.1	39.1	52.2	65.2	78.3	94.0	104
1.35	¼		15.8	18.4	21.1	26.4	39.6	52.8	66.0	79.2	95.0	105
1.36	16⅜		16.0	18.6	21.3	26.7	40.0	53.4	66.7	80.0	96.1	106
1.37	½		16.2	18.9	21.5	26.9	40.4	53.9	67.4	80.9	97.1	107
1.38	9-16		16.3	19.1	21.8	27.2	40.9	54.5	68.2	81.8	98.2	109
1.39	⅝		16.5	19.3	22.0	27.5	41.3	55.1	68.9	82.7	99.3	110.
1.40	¾		16.7	19.5	22.3	27.8	41.8	55.7	69.7	83.6	100	111
1.41	16⅞		16.9	19.7	22.5	28.1	42.2	56.3	70.4	84.5	101	112
1.42	17		17.0	19.9	22.7	28.4	42.7	56.9	71.2	85.4	102	113
1.43	⅛		17.2	20.1	23.0	28.7	43.1	57.5	71.9	86.3	103	115
1.44	¼		17.4	20.3	23.2	29.0	43.6	58.1	72.7	87.2	104	116
1.45	⅜		17.6	20.5	23.5	29.3	44.0	58.7	73.4	88.1	105	117
1.46	17½	...	17.8	20.7	23.7	29.7	44.5	59.3	74.2	89.0	106	118
1.47	⅝		18.0	21.0	24.0	30.0	45.0	60.0	75.0	90.0	108.	120
1.48	¾		18.1	21.2	24.2	30.3	45.4	60.6	75.7	90.9	109	121
1.49	⅞		18.3	21.4	24.4	30.6	45.9	61.2	76.5	91.8	110	122
1.50	18		18.5	21.6	24.7	30.9	46.3	61.8	77.3	92.7	111.	123

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR—Continued

For Various Lengths and Depths **Formula: Q equals 3.367 LH 3-2**

Head "H" on crest Measured in Still Water		Length of Weir Crest in Feet								
		Discharge in Cubic Feet per Second								
Feet In.	Inches Approx.	3½	4	5	7½	10	12½	15	18	20
1.51	18⅛	21.8	24.9	31.2	46.8	62.4	78.0	93.7	112.	124.
1.52	¼	22.0	25.2	31.5	47.3	63.0	78.8	94.6	113.	126.
1.53	⅜	22 3	25 4	31.8	47.7	63.7	79 6	95.5	114	127
1.54	½	22.5	25.7	32.1	48.2	64.3	80.4	96.5	115.	128.
1.55	⅝	22.7	25.9	32.4	48.7	64.9	81.2	97.4	116.	129.
1 56	18¾	22.9	26.2	32.8	49.2	65.6	82.0	98.4	118.	131.
1.57	⅞	23.1	26.4	33.1	49.6	66.2	82.7	99.3	119.	132
1.58	19	23 4	26.7	33.4	50.1	66.8	83.5	100.	120.	133.
1.59	⅛	23.6	27.0	33.7	50.6	67.5	84.3	101.	121.	135
1.60	¼	23.8	27.2	34.0	51.1	68.1	85.1	102.	122.	136.
1.61	19⅜	24.0	27.5	34.3	51.5	68.7	85.9	103.	123.	137.
1 62	½	24.3	27.7	34.7	52.0	69.4	86 7	104	124	138
1.63	9-16	24.5	28.0	35.0	52.5	70.0	87.5	105.	126	140.
1 64	⅝	24.7	28.2	35.3	53.0	70.7	88.3	106	127.	141
1.65	¾	24.9	28.5	35.6	53.5	71.3	89.1	107	128.	142.
1.66	19⅞	25.2	28 8	36.0	54.0	72.0	90 0	108	129	144
1.67	20	25.4	29.0	36.3	54.4	72.6	90.8	108.	130	145
1.68	⅛	25.6	29.3	36.6	54.9	73.3	91.6	109.	131.	146.
1 69	¼	25.8	29.5	36.9	55.4	73.9	92.4	110.	133.	147
1.70	⅜	26.1	29 8	37.3	55.9	74.6	93 2	111.	134	149
1 71	20½	26.3	30.1	37 6	56 4	75.2	94.1	112.	135	150.
1.72	⅝	26.5	30.3	37.9	56 9	75.9	94.9	113.	136.	151
1 73	¾	26.8	30 6	38.3	57.4	76.6	95.7	114.	137.	153.
1.74	⅞	27.0	30.9	38.6	57.9	77.2	96.5	115.	139	154
1.75	21	27.2	31.1	38.9	58.4	77.9	97.4	116	140	155
1.76	21⅛	27.5	31.4	39.3	58.9	78 6	98.2	117.	141.	157.
1 77	¼	27.7	31.7	39.6	59.4	79.2	99.1	118.	142.	158
1.78	⅜	27.9	31 9	39.9	59 9	79.9	99.9	119.	143	159
1.79	½	28.2	32 2	40 3	60 4	80.6	100.	120.	145	161
1.80	⅝	28.4	32.5	40.6	60.9	81.3	101.	121.	146	162.
1.81	21¾	.....	32.7	40.9	61.4	81.9	102.	122.	147	163
1.82	⅞	.....	33.0	41 3	62.0	82.6	103.	123.	148.	165
1.83	22	....	33.3	41.6	62.5	83.3	104.	125.	150	166
1 84	⅛	.....	33.6	42.0	63.0	84.0	105.	126	151	168
1.85	¼	.....	33 8	42.3	63.5	84.7	105.	127.	152	169.
1.86	22⅜	.....	34.1	42.7	64.0	85.4	106.	128.	153.	170
1.87	½	.....	34.4	43.0	64.5	86.0	107.	129.	154	172
1.88	9-16	.....	34 7	43.3	65.0	86.7	108.	130	156	173
1.89	⅝	.....	34.9	43 7	65.6	87.4	109.	131.	157.	174.
1.90	¾	....	35.2	44.0	66.1	88.1	110.	132.	158.	176
1.91	22⅞	.....	35.5	44.4	66.6	88.8	111.	133.	159.	177.
1.92	23	.....	35.8	44.7	67.1	89.5	111.	134.	161.	179.
1.93	⅛	.....	36.1	45.1	67.7	90.2	112.	135.	162.	180.
1.94	¼	.....	36.3	45.4	68.2	90 9	113.	136.	163.	181.
1.95	⅜	....	36 6	45.8	68.7	91.6	114.	137	165	183.
1.96	23½	.....	36 9	46.1	69.2	92.3	115.	138.	166	184.
1.97	⅝	.....	37.2	46.5	69.8	93.0	116.	139.	167.	186.
1.98	¾	.....	37 5	46 9	70.3	93 8	117	140.	168.	187.
1.99	⅞	.....	37.8	47.2	70.8	94.5	118.	141.	170.	189
2.00	24	.....	38.0	47.6	71.4	95.2	119.	142.	171.	190.

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR—Continued

For Various Lengths and Depths Formula: Q equals 3.367 LH 3-2

Head "H" on crest Measured in Still Water		Discharge in Cubic Feet per Second					
		Length of Weir Crest in Feet					
Feet	Inches Approx.	7½	10	12½	15	18	20
2.51	30⅛	100.	133.	167.	200.	240	267
2.52	¼	101.	134.	168.	202.	242.	269.
2.53	⅜	101	135.	169.	203.	243	270
2.54	½	102.	136.	170.	204.	245	272
2.55	⅝	102.	137.	171	205.	246.	274.
2.56	30¾	103	137.	172.	206.	248.	275.
2.57	⅞	104.	138	173.	208.	249.	277.
2.58	31	104.	139.	174.	209.	251.	279.
2.59	⅛	105.	140.	175.	210.	252.	280.
2.60	¼	105.	141.	176.	211	254.	282.
2.61	31⅜	106.	141.	177.	212.	255.	283.
2.62	½	107	142.	178.	214.	256.	285.
2.63	9-16	107.	143.	179.	215.	258.	287.
2.64	⅝	108.	144.	180.	216.	259.	288.
2.65	¾	108	145.	181	217.	261.	290.
2.66	31⅞	109.	146	182.	219.	262.	292.
2.67	32	110.	146	183	220	264	293.
2.68	⅛	110.	147.	184.	221.	265.	295.
2.69	¼	111	148	185	222	267.	297
2.70	⅜	112	149	186	224	268	298
2.71	32½	112.	150.	187.	225.	270.	300.
2.72	⅝	113.	151	188	226.	271.	302
2.73	¾	113.	151.	189	227	273.	303.
2.74	⅞	114.	152.	190	229.	274.	305
2.75	33	115.	153	191	230.	276	307
2.76	33⅛	115.	154	192	231	277	308
2.77	¼	116	155	194.	232.	279	310.
2.78	⅜	117	156	195	234	280	312.
2.79	½	117.	156	196	235.	282	313
2.80	⅝	118.	157.	197	236.	283	315.
2.81	33¾	118	158.	198.	237.	285.	317.
2.82	⅞	119	159.	199.	239.	286.	318
2.83	34	120.	160	200.	240.	288	320
2.84	⅛	120	161	201	241	290	322
2.85	¼	121	161	202	242.	291	323.
2.86	34⅜	122	162	203.	244.	293.	325.
2.87	½	122	163	204.	245	294.	327.
2.88	9-16	123	164.	205.	246.	296.	329.
2.89	⅝	124.	165	206	248	297	330.
2.90	¾	124.	166	207.	249.	299.	332.
2.91	34⅞	125	167.	208.	250.	300.	334.
2.92	35	125.	167.	209.	251.	302.	335.
2.93	⅛	126.	168	211	253.	303.	337.
2.94	¼	127	169	212	254.	305	339
2.95	⅜	127.	170.	213.	255.	307	341
2.96	35½	128	171.	214.	257.	308.	342.
2.97	⅝	129.	172.	215.	258.	310.	344.
2.98	¾	129.	173.	216	259.	311.	346.
2.99	⅞	130.	174.	217.	261.	313.	348.
3.00	36	131.	174	218	262	314.	349

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIR—Continued

For Various Lengths and Depths Formula: Q equals 3.367 LH 3-2

Head "H" on Crest Measured in Still Water		Discharge in Cubic Feet per Second							
		Length of Weir Crest in Feet							
Feet	Inches Approx.	4	5	7½	10	12½	15	18	20
2.01	24⅛	38.3	47.9	71.9	95.9	119.	143.	172.	191.
2.02	¼	38.6	48.3	72.4	96.6	120.	144.	173.	193.
2.03	⅜	38.9	48.6	73.0	97.3	121.	146.	175.	195
2.04	½	39.2	49.0	73.5	98.0	122.	147.	176	196.
2.05	⅝	39.5	49.4	74.1	98.8	123.	148.	177.	197
2.06	24¾	39.8	49.7	74.6	99.5	124.	149	179.	199
2.07	⅞	40.1	50.1	75.2	100	125.	150.	180.	200
2.08	25	40.4	50.5	75.7	100	126.	151.	181	201
2.09	⅛	40.6	50.8	76.2	101.	127.	152.	183	203
2.10	¼	40.9	51.2	76.8	102	128.	153.	184	204
2.11	25⅜		51.5	77.3	103	128	154	185.	206
2.12	½		51.9	77.9	103	129	155.	187.	207
2.13	9-16		52.3	78.4	104.	130.	156.	188	209
2.14	⅝		52.7	79.0	105.	131.	158.	189.	210
2.15	¾		53.0	79.6	106	132.	159.	191.	212
2.16	25⅞		53.4	80.1	106	133.	160	192.	213
2.17	26		53.8	80.7	107.	134	161.	193.	215
2.18	⅛		54.1	81.2	108.	135.	162	195.	216
2.19	¼		54.5	82.8	109	136.	163.	196	218
2.20	⅜		54.9	82.3	109	137.	164.	197.	219
2.21	26½		55.3	82.9	110	138	165	199	221
2.22	⅝		55.6	83.5	111	139	167.	200	222.
2.23	¾		56.0	84.0	112	140	168	201	224
2.24	⅞		56.4	84.6	112.	141.	169	203.	225
2.25	27		56.8	85.2	113	142.	170	204	227
2.26	27⅛		57.1	85.7	114.	142	171	205	228
2.27	¼		57.5	86.3	115	143	172.	207	230.
2.28	⅜		57.9	86.9	115	144	173.	208.	231
2.29	½		58.3	87.5	116	145.	175	210	233
2.30	⅝		58.7	88.0	117	146	176	211	234
2.31	27¾		59.1	88.6	118	147	177	212.	236
2.32	⅞		59.4	89.2	118.	148	178.	214.	237
2.33	28		59.8	89.8	119.	149	179	215	239
2.34	⅛		60.2	90.3	120.	150.	180.	216.	241.
2.35	¼		60.6	90.9	121	151	181	218.	242
2.36	28⅜		61.0	91.5	122	152	183	219.	244
2.37	½		61.4	92.1	122.	153	184	221	245
2.38	9 16		61.8	92.7	123	154	185	222	247
2.39	⅝		62.2	93.3	124	155	[illegible]	[illegible]	[illegible]
2.40	¾		62.5	93.8	125	156.	187	225.	250
2.41	28⅞			94.4	125	157.	188.	226.	251
2.42	29			95.0	126	158.	190.	228.	253.
2.43	⅛			95.6	127	159.	191	229.	255
2.44	¼			96.2	128	160.	192	230.	256.
2.45	⅜			96.8	129	161.	193.	232	258
2.46	29½			97.4	129.	162.	194.	233.	259.
2.47	⅝			98.0	130	163.	196.	235.	261.
2.48	¾			98.6	131	164.	197.	236.	262.
2.49	⅞			99.2	132	165.	198.	238	264.
2.50	30			99.8	133	166.	199	239.	266

TABLE NUMBER II

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIRS

In Cubic Feet per Second and Equivalent Acre Feet per 24 Hours

Approximate depth on Weir in inches	Depth on Weir in feet	Length of Weir in Inches					
		6 Inches		12 Inches		18 Inches	
		Cu. ft. per sec	Acre ft per 24 hours	Cu. ft. per sec.	Acre ft per 24 hours	Cu ft. per sec	Acre ft per 24 hrs
⅛	01	0 002	0.003	0 003	0 007	0 005	0.010
¼	.02	.005	.009	.010	.019	.014	.028
⅜	.03	.009	017	.018	.035	026	052
½	.04	013	.027	027	053	040	.080
⅝	.05	.019	037	.038	075	.056	.112
¾	06	.025	.049	.050	.098	.074	.147
13-16	07	031	062	062	124	093	186
15-16	08	038	076	076	.151	.114	.227
1 1-16	09	.045	.090	.091	.180	.136	.270
1 3-16	10	.053	106	.107	211	160	.317
1 5-16	11	.061	122	123	.244	.184	.365
1 7-16	.12	070	.139	.140	.278	.210	.416
1 9-16	13	079	.157	158	.313	.237	.470
1 11 16	.14	088	.175	.176	.350	.265	525
1 13 16	15	098	194	196	388	293	582
1 15-16	16	108	214	216	427	323	641
2 1-16	17	118	234	.236	468	354	.702
2 3-16	18	129	255	257	510	.386	.765
2¼	.19	139	277	279	553	.418	.830
2⅜	20	151	299	301	597	452	896
2½	21	162	321	324	643	.486	964
2⅝	22	174	345	347	689	521	1 03
2¾	23	186	368	371	737	557	1 10
2⅞	.24	198	393	396	785	594	1 17
3	25	210	417	421	835	631	1 25
3⅛	26			446	885	669	1.32
3¼	27			472	937	.709	1 40
3⅜	28	..	.	499	989	.748	1 48
3½	29			526	1 04	.789	1.56
3⅝	30		.	553	1.09	.830	1.64
3¾	31	.	.	581	1.15	.872	1 72
3 13-16	32			609	1 20	.914	1 81
3 15-16	33	.	.	638	1 26	.957	1.89
4 1 16	.34		.	667	1 32	1.00	1.98
4 3-16	35	.		.697	1 38	1 04	2.07
4 5 16	36			727	1.44	1.09	2.16
4 7 16	37	.	.	758	1 50	1.13	2.25
4 9 16	38			789	1 56	1.18	2 34
4 11-16	39			820	1 62	1.23	2 44
4 13-16	.40			852	1 68	1.27	2.53
4 15-16	41	.	..	884	1 75	1.32	2 63
5 1-16	.42		.	916	1 81	1.37	2 72
5 3-16	43	. .	.	949	1 88	1 42	2 82
5¼	44	.		983	1.94	1.47	2.92
5⅜	45			1 01	2.01	1 52	3.02
5½	46	..	.	1.05	2 08	1 57	3 12
5⅝	.47	..	...	1 08	2.15	1 62	3.22
5¾	48	..	.	1 12	2 22	1 67	3 33
5⅞	.49	.	...	1.15	2.29	1.73	3.43
6	50	...	..	1 19	2.36	1.78	3.54

TABLE NUMBER II—Continued

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIRS

In Cubic Feet per Second and Equivalent Acre Feet per 24 Hours

Approximate depth on weir in Inches	Depth on weir in feet	Length of Weir in Inches					
		6 Inches		12 Inches		18 Inches	
		Cu. ft. per sec.	Acre ft. per 24 hours	Cu. ft. per sec.	Acre ft. per 24 hours	Cu. ft. per sec.	Acre ft. per 24 hours
6⅛	.51	....	....	....	....	1.83	3.64
6¼	.52	....	....	....	....	1.89	3.75
6⅜	.53	....	....	....	....	1.94	3.86
6½	.54	....	....	....	....	2.00	3.97
6⅝	.55	....	....	....	....	2.06	4.08
6¾	56	....	....	....	....	2.11	4.19
6 13-16	.57	....	....	....	....	2.17	4.31
6 15-16	.58	....	....	....	....	2.23	4.42
7 1-16	.59	....	....	....	....	2.28	4.53
7 3-16	.60	....	....	....	....	2.34	4.65
7 5-16	.61	....	....	....	....	2.40	4.77
7 7-16	.62	....	....	....	....	2.46	4.89
7 9-16	.63	....	....	....	....	2.52	5.00
7 11-16	.64	....	....	....	....	2.58	5.12
7 13-16	65	....	....	....	....	2 64	5.24
7 15-16	66	....	....	....	....	2.70	5 37
8 1-16	.67	....	....	....	....	2.77	5.49
8 3-16	.68	....	....	....	....	2.83	5.61
8¼	.69	....	....	....	....	2 89	5.74
8⅜	.70	....	....	....	....	2.95	5.86
8½	.71	....	....	....	....	3.02	5.99
8⅝	.72	....	....	....	....	3.08	6.11
8¾	.73	....	....	....	....	3.15	6.24
8⅞	.74	....	....	....	....	3 21	6.37
9	.75	....	....	....	....	3.28	6 50
9⅛	76	....	....	....	....	....	....
9¼	.77	....	....	....	....	....	....
9⅜	.78	....	....	....	....	....	....
9½	.79	....	....	....	....	....	....
9⅝	80	....	....	....	....	....	....
9¾	.81	....	....	....	....	....	....
9 13-16	.82	....	....	....	....	....	....
9 15-16	.83	....	....	....	....	....	....
10 1-16	.84	....	....	....	....	....	....
10 3-16	.85	....	....	....	....	....	....
10 5-16	.86	....	....	....	....	....	....
10 7-16	.87	....	....	....	....	....	....
10 9-16	88	....	....	....	....	....	....
10 11-16	.89	....	....	....	....	....	....
10 13-16	.90	....	....	....	....	....	....
10 15-16	.91	....	....	....	....	....	....
11 1-16	.92	....	....	....	....	....	....
11 3-16	.93	....	....	....	....	....	....
11⅛	94	....	....	....	....	....	....
11⅜	.95	....	....	....	....	....	....
11½	.96	....	....	....	....	....	....
11⅝	.97	....	....	....	....	....	....
11¾	.98	....	....	....	....	....	....
11⅞	.99	....	....	....	....	....	....
12	1 00	....	....	....	....	....	....

TABLE NUMBER II—Continued

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIRS

In Cubic Feet per Second and Equivalent Acre Feet per 24 Hours

Approximate depth on weir in inches	Depth on weir in feet	Length of Weir in Inches							
		24 Inches		30 Inches		48 Inches		36 Inches	
		Cu. ft. per sec.	Acre ft. per 24 hrs.	Cu. ft. per sec	Acre ft. per 24 hrs.	Cu. ft. per sec.	Acre ft. per 24 hrs.	Cu. ft per sec	Acre ft per 24 hrs
1/8	01	.007	.013	008	016	.010	.020	013	026
1/4	02	.019	.038	.024	.047	.029	.057	038	075
3/8	.03	.035	.069	.044	.087	.053	.104	.070	.139
1/2	.04	.054	.107	.067	.133	.081	.161	.108	.213
5/8	.05	.075	.149	.094	.187	.113	224	.151	.299
3/4	.06	099	.196	.124	.245	148	294	.198	.393
13-16	.07	.125	247	.156	.309	.187	371	.249	495
15-16	.08	.152	.302	.191	.378	229	.453	305	.604
1 1-16	.09	.182	.361	227	.451	.273	.541	.364	721
1 3-16	.10	.213	422	266	528	319	633	426	845
1 5-16	.11	246	487	307	.609	369	731	491	974
1 7-16	.12	.280	.555	.350	694	.420	.833	.560	1.11
1 9-16	.13	.316	620	.395	.782	.473	939	631	1.25
1 11-16	.14	353	700	441	874	529	1 04	705	1 39
1 13-16	.15	391	776	.489	970	.587	1 16	782	1 55
1 15-16	.16	.431	855	.539	1 06	646	1 28	.862	1 70
2 1-16	17	472	936	590	1 17	708	1 40	944	1 87
2 3-16	18	.514	1 02	.643	1.27	771	1 52	1 02	2.03
2 1/4	19	558	1 10	.697	1 38	837	1.65	1.11	2.21
2 3/8	.20	602	1 19	.753	1.49	.903	1 79	1.20	2.38
2 1/2	.21	648	1.28	.810	1 60	972	1.92	1.29	2.57
2 5/8	22	695	1.37	869	1 72	1 04	2 06	1 39	2.75
2 3/4	.23	743	1.47	928	1 84	1 11	2 21	1 48	2.94
2 7/8	.24	792	1 57	990	1 96	1 18	2 35	1.58	3.14
3	25	842	1 66	1 05	2 08	1 26	2 50	1 68	3 33
3 1/8	26	893	1.77	1 11	2 21	1.33	2.65	1 78	3.54
3 1/4	.27	945	1 87	1 18	2 34	1.41	2 81	1.88	3.74
3 3/8	28	998	1 97	1.24	2 47	1 49	2 96	1.99	3 95
3 1/2	29	1 05	2 08	1 31	2 60	1 57	3 12	2 10	4.17
3 5/8	30	1 10	2 19	1 38	2 74	1.66	3.29	2 21	4.38
3 3/4	31	1.16	2 30	1 45	2 88	1 74	3 45	2 32	4 61
3 13-16	32	1 21	2 41	1 52	3 02	1.82	3 62	2 43	4 83
3 15-16	33	1 27	2 53	1 59	3 16	1 91	3 79	2 55	5 06
4 1-16	.34	1 33	2 64	1 66	3.31	2.00	3 97	2.67	5 29
4 3-16	35	1.39	2 76	1 74	3 45	2 09	4 14	2 78	5.53
4 5-16	36	1 45	2 88	1 81	3.60	2 18	4 32	2.90	5 76
4 7-16	.37	1 51	3 00	1.89	3 75	2 27	4 50	3 03	6.01
4 9-16	38	1.57	3 12	1 97	3 91	2 36	4 69	3 15	6 25
4 11-16	39	1 64	3 25	2.05	4 06	2 46	4 87	3 28	6.50
4 13-16	40	1 70	3 37	2 12	4 22	2 55	5 06	3 40	6 75
4 15-16	41	1 76	3 50	2 21	4 38	2 65	5.25	3 53	7.01
5 1-16	.42	1 83	3 63	2 29	4 54	2 74	5 45	3 66	7 27
5 3-16	.43	1 89	3 76	2.37	4.70	2 84	5 64	3 79	7 53
5 1/4	44	1 96	3 89	2.45	4 87	2.94	5 84	3 90	7 79
5 3/8	.45	2.03	4 03	2 54	5.03	3 04	6 04	4 06	8 06
5 1/2	46	2 10	4.16	2.62	5 20	3 15	6 25	4.20	8 33
5 5/8	.47	2.17	4 30	2.71	5 37	3.25	6.45	4.33	8.60
5 3/4	.48	2 23	4 44	2 79	5.55	3 35	6.66	4 47	8.88
5 7/8	.49	2.30	4.58	2.88	5.72	3 46	6 87	4.61	9.16
6	50	2 38	4.72	2 97	5.90	3 57	7.08	4 76	9 44

TABLE NUMBER II—Continued

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIRS

In Cubic Feet per Second and Equivalent Acre Feet per 24 Hours

Approximate depth on weir in inches	Depth on weir in feet	Length of Weir in Inches							
		24 Inches		30 Inches		36 Inches		48 Inches	
		Cu. ft per sec	Acre ft. per 24 hrs.	Cu ft per sec.	Acre f per 24 hrs.	Cu. ft. per sec.	Acre ft. per 24 hrs.	Cu ft per sec	Acre ft per 24 hrs
6 1/8	.51	2.45	4.86	3.06	6.0	3.67	7.2	4.9	9.7
6 1/4	.52	2.52	5.00	3.15	6.2	3.78	7.5	5.0	10.0
6 3/8	.53	2.59	5.15	3.24	6.4	3.89	7.7	5.1	10.3
6 1/2	.54	2.67	5.30	3.34	6.6	4.00	7.9	5.3	10.5
6 5/8	.55	2.74	5.44	3.43	6.8	4.12	8.1	5.4	10.8
6 3/4	.56	2.82	5.59	3.52	6.9	4.23	8.3	5.6	11.1
6 13-16	.57	2.89	5.74	3.62	7.1	4.34	8.6	5.7	11.4
6 15-16	.58	2.97	5.89	3.71	7.3	4.46	8.8	5.9	11.7
7 1-16	.59	3.05	6.05	3.81	7.5	4.57	9.0	6.1	12.1
7 3-16	.60	3.12	6.20	3.91	7.7	4.69	9.3	6.2	12.4
7 5-16	.61	3.20	6.36	4.01	7.9	4.81	9.5	6.4	12.7
7 7-16	.62	3.28	6.52	4.10	8.1	4.93	9.7	6.5	13.0
7 9-16	.63	3.36	6.67	4.20	8.3	5.05	10.0	6.7	13.3
7 11-16	.64	3.44	6.83	4.30	8.5	5.17	10.2	6.8	13.6
7 13-16	.65	3.52	6.99	4.41	8.7	5.29	10.4	7.0	13.9
7 15-16	.66	3.61	7.16	4.51	8.9	5.41	10.7	7.2	14.3
8 1-16	.67	3.69	7.32	4.61	9.1	5.53	10.9	7.3	14.6
8 3-16	.68	3.77	7.48	4.72	9.3	5.66	11.2	7.5	14.9
8 1/4	.69	3.85	7.65	4.82	9.5	5.78	11.4	7.7	15.3
8 3/8	.70	3.94	7.82	4.92	9.7	5.91	11.7	7.8	15.6
8 1/2	.71	4.02	7.99	5.03	9.9	6.04	11.9	8.0	15.9
8 5/8	.72	4.11	8.15	5.14	10.1	6.17	12.2	8.2	16.3
8 3/4	.73	4.20	8.33	5.25	10.4	6.30	12.4	8.3	16.6
8 7/8	.74	4.28	8.50	5.35	10.6	6.42	12.7	8.5	17.0
9	.75	4.37	8.67	5.46	10.8	6.56	13.0	8.7	17.3
9 1/8	.76			5.57	11.0	6.69	13.2	8.9	17.6
9 1/4	.77			5.68	11.2	6.82	13.5	9.0	18.0
9 3/8	.78			5.79	11.5	6.95	13.8	9.2	18.4
9 1/2	.79			5.91	11.7	7.09	14.0	9.4	18.7
9 5/8	.80			6.02	11.9	7.22	14.3	9.6	19.1
9 3/4	.81			6.13	12.1	7.36	14.6	9.8	19.4
9 13-16	.82			6.25	12.3	7.50	14.8	10.0	19.8
9 15-16	.83			6.36	12.6	7.63	15.1	10.1	20.1
10 1-16	.84			6.48	12.8	7.77	15.4	10.3	20.5
10 3-16	.85			6.59	13.0	7.91	15.6	10.5	20.9
10 5-16	.86			6.71	13.3	8.05	15.9	10.7	21.3
10 7-16	.87			6.83	13.5	8.19	15.9	10.9	21.6
10 9-16	.88			6.94	13.7	8.33	16.5	11.1	22.0
10 11-16	.89			7.06	14.0	8.48	16.8	11.3	22.4
10 13-16	.90			7.18	14.2	8.62	17.1	11.4	22.8
10 15-16	.91			7.30	14.4	8.76	17.3	11.6	23.1
11 1-16	.92			7.42	14.7	8.91	17.6	11.8	23.5
11 3-16	.93			7.54	14.9	9.05	17.9	12.0	23.9
11 1/4	.94			7.67	15.2	9.20	18.2	12.2	24.3
11 3/8	.95			7.79	15.4	9.35	18.5	12.4	24.7
11 1/2	.96			7.91	15.7	9.50	18.8	12.6	25.1
11 5/8	.97			8.04	15.9	9.64	19.1	12.8	25.5
11 3/4	.98			8.16	16.1	9.79	19.4	13.0	25.9
11 7/8	.99			8.29	16.4	9.94	19.7	13.2	26.3
12	1.00			8.41	16.6	10.10	20.0	13.4	26.7

TABLE NUMBER II—Continued

DISCHARGE OVER CIPPOLETTI TRAPEZOIDAL WEIRS

In Cubic Feet per Second and Equivalent Acre Feet per 24 Hours

Approximate depth on weir in inches	Depth on weir in feet	Length of Weir in Inches					
		30 Inches		36 Inches		48 Inches	
		Cu ft. per sec.	Acre ft. per 24 hours	Cu. ft. per sec.	Acre ft. per 24 hours	Cu. ft. per sec.	Acre ft. per 24 hours
12⅛	1.01	8.54	16.9	10.2	20.3	13.6	27.1
12¼	1.02	8.67	17.1	10.4	20.6	13.8	27.5
12⅜	1.03	8.79	17.4	10.5	20.9	14.0	27.9
12½	1.04	8.92	17.7	10.7	21.2	14.2	28.3
12⅝	1.05	9.05	17.9	10.8	21.5	14.4	28.7
12¾	1.06	9.18	18.2	11.0	21.8	14.6	29.1
12 13-16	1.07	9.31	18.4	11.1	22.1	14.9	29.5
12 15-16	1.08	9.44	18.7	11.3	22.4	15.1	29.9
13 1-16	1.09	9.57	18.9	11.4	22.7	15.3	30.3
13 3-16	1.10	9.71	19.2	11.6	23.1	15.5	30.8
13 5-16	1.11	9.84	19.5	11.8	23.4	15.7	31.2
13 7-16	1.12	9.97	19.7	11.9	23.7	15.9	31.6
13 9-16	1.13	10.1	20.0	12.1	24.0	16.1	32.0
13 11-16	1.14	10.2	20.3	12.2	24.3	16.3	32.5
13 13-16	1.15	10.3	20.5	12.4	24.7	16.6	32.9
13 15-16	1.16	10.5	20.8	12.6	25.0	16.8	33.3
14 1-16	1.17	10.6	21.1	12.7	25.3	17.0	33.8
14 3-16	1.18	10.7	21.3	12.9	25.6	17.2	34.2
14¼	1.19	10.9	21.6	13.1	26.0	17.4	34.6
14⅜	1.20	11.0	21.9	13.2	26.3	17.7	35.1
14½	1.21			13.4	26.6	17.9	35.5
14⅝	1.22			13.6	26.9	18.1	35.9
14¾	1.23			13.7	27.3	18.3	36.4
14⅞	1.24			13.9	27.6	18.5	36.8
15	1.25			14.1	27.9	18.8	37.3
15⅛	1.26			14.2	28.3	19.0	37.7
15¼	1.27			14.4	28.6	19.2	38.2
15⅜	1.28			14.6	29.0	19.5	38.6
15½	1.29			14.7	29.3	19.7	39.1
15⅝	1.30			14.9	29.6	19.9	39.5
15¾	1.31			15.1	30.0	20.1	40.0
15 13-16	1.32			15.3	30.3	20.4	40.5
15 15-16	1.33			15.4	30.7	20.6	40.9
16 1-16	1.34			15.6	31.0	20.8	41.4
16 3-16	1.35			15.8	31.4	21.1	41.8
16 5-16	1.36			16.0	31.7	21.3	42.3
16 7-16	1.37			16.1	32.1	21.5	42.8
16 9-16	1.38			16.3	32.4	21.8	43.3
16 11-16	1.39			16.5	32.8	22.0	43.7
16 13-16	1.40			16.7	33.1	22.3	44.2
16 15-16	1.41			16.9	33.5	22.5	44.7
17 1-16	1.42			17.0	33.8	22.7	45.1
17 3-16	1.43			17.2	34.2	23.0	45.6
17⅛	1.44			17.4	34.6	23.2	46.1
17⅜	1.45			17.6	34.9	23.5	46.6
17½	1.46			17.8	35.3	23.7	47.1
17⅝	1.47			18.0	25.7	24.0	47.6
17¾	1.48			18.1	36.0	24.2	48.0
17⅞	1.49			18.3	36.4	24.4	48.5
18	1.50			18.5	36.8	24.7	49.0

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2-17-27-3M Printed by the College Printing Department 644

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 11 Sept., 1928 No. 4

An Extensometer and Compressometer of the Hydro-Static Type

by

Howard H. Langdon

ENGINEERING BULLETIN NO. 25

ENGINEERING EXPERIMENT STATION

October, 1928

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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AN EXTENSOMETER AND COMPRESSOMETER OF THE HYDRO-STATIC TYPE

INTRODUCTION

In order to study the physical properties of the materials used in construction, it is necessary to measure the changes in their length caused by known changes in tensile or compressive stresses applied to them

These changes in length are very small and require accurate measurements which have been accomplished in the past (1) by direct mechanical means such as a system of multiplying levers or trains of gears operating indicating dials all of which are combined into a compact instrument that is clamped over a definite length of the specimen or structural member to be tested; (2) by combining optical systems such as the micrometer miscroscope or the mirror type optical lever with suitable clamping devices to form a magnifying extensometer All of these depend upon direct lever ratios or combined lever and light beam magnification in simple ratio.

The instrument here described was designed and constructed in the laboratory and shops of the State College of Washington, and operates on the hydro-static principle It has the advantages that (1) it compensates accurately for bending action of the specimen within the gage length while many of the mechanical types that clamp on one side or one face of the member to be tested are affected by bending or column action; (2) it can be readily changed to different magnifying powers to suit the particular accuracy needed, reading with good accuracy and sensitivity in each case, even to one millionth part of an inch, (3) it is flexible and easily and quickly set up where many similar specimens are to be tested, such as concrete cylinders from construction jobs.

DESCRIPTION

The instrument works on the hydro-static principle that a definite quantity of liquid tends to maintain its volume constant. It consists essentially of one or more flexible metallic bellows filled with a suitable liquid and so arranged that the change in dimension to be measured causes a change of length in these bellows. If the bellows are compressed, liquid is forced out into a gage glass of small diameter so that the change in length of the bellows is greatly magnified. This magnification is the ratio of the total cross sectional area of the bellows to the cross sectional area of the inside of the gage tube used. This ratio, stated in another way, is the ratio of the square of the diameter of the bellows multiplied by the number of bellows used to the square of the diameter of the glass tube into which the liquid is forced.

The general arrangement of the apparatus as used for determining the change of length of concrete cylinders is shown in figure 1 and consists of two parts: the actuating part that is clamped on the concrete cylinder, and the reading or gage board.

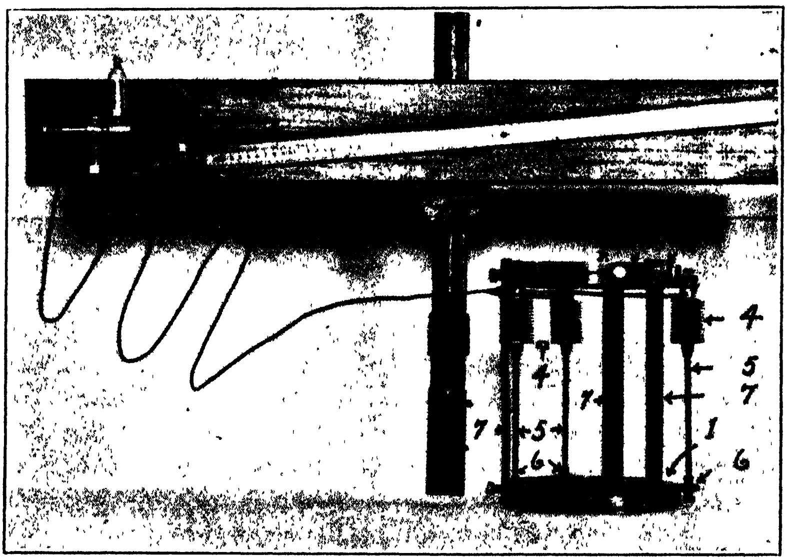


Figure 1. View of the Complete Instrument as Constructed for Compression Tests of Concrete Cylinders

The actuating mechanism consists of two rings, parts 1-1, Fig. 1, which are clamped to the cylinder at the proper gage length, (ten inches as illustrated), by three set screws in each ring, shown as part 2, Fig. 2. The set screws are clamped tight in their threads by cap screws, shown as part 3, Fig. 1. Between the clamping rings are three equally spaced metallic bellows, parts 4-4-4, Fig. 1-2, attached to ears on the clamping rings. The upper end caps of the

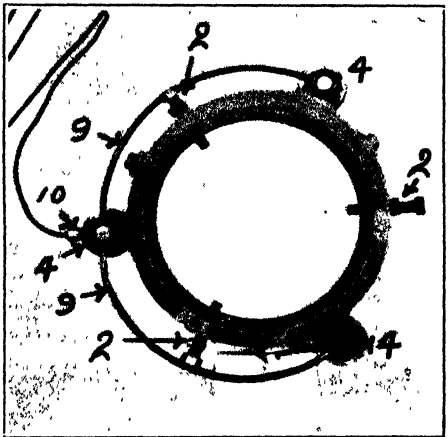


Figure 2 End View of Actual Mechanism, Showing the Relative Position of the Bellows, Clamping Screws, Spacing Bars and Connecting Tubes.

bellows are bolted solidly to the ears of the upper ring while the lower end caps are drilled and threaded to receive a ¼ inch round rod, shown as parts 5-5-5, Fig. 1, which pass down to the ears on the bottom end and have a spherical seat adjusted with spring pressure shown at point 6, Fig. 1. This allows for self alignment and causes minimum distortion of the bellows.

Three spacing bars, shown as parts 7-7-7, Fig. 1, welded to the bottom ring and with the double shoulders at the upper end, are for the purpose of spacing and holding the clamping rings at the proper gage length when the instrument is not in use and while setting up. When clamped to the cylinder the cap screws at the upper end, parts 8-8-8, Fig. 1, are loosened and the spacing rods spring away from the upper clamping ring allowing the clamping rings to move with the concrete during the test.

Small metal tubes, parts 9-9, Fig. 2, pass between the three bellows and have direct connection to the liquid inside, allowing free flow of liquid between the bellows.

At the central bellows a connecting fitting, point 10, Fig. 2, is inserted into the liquid system and a tube passes from this fitting to the gage board. This tube is small and flexible allowing the gage board to be set at a convenient distance from the actuating mechanism.

The gage board is fitted with a valve body, a reservoir, a bi-liquid reservoir, a gage glass, and a scale.

The valve body, part 1, Fig. 3, contains a needle valve for the reservoir, part 2, Fig. 3, an adjusting piston, part 3, Fig. 3, which allows adjustment of the liquid column to zero, and a needle valve, part 8, Fig. 3, to cut out both the adjusting piston and reservoir so that communication is direct from the actuating mechanism to the gage glass. The reservoir, part 4, Fig. 3, when open to the system allows the free flow of liquid from the actuating bellows to the reservoir and permits the adjustment of the clamping rings without loss

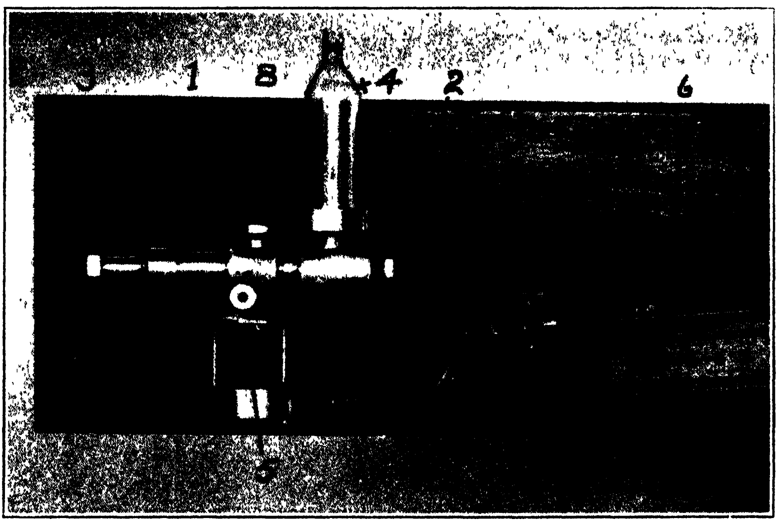


Figure 3. View Showing Gage Board.

of liquid from the system and prevents air from entering the system through the gage glass. It is always open except during the actual reading period.

The bi-liquid reservoir, part 5, Fig. 3, is for the purpose of using a desirable liquid in the gage glass different from the liquid in the bellows system Because of its low coefficient of expansion, and chemical inactivity, it is desirable to have distilled water in the bellows system.

Carbon tetra-chloride diluted to a specific gravity of about 1.5 with benzene and colored with "pitot red" is a desirable liquid in the gage glass. The bi-liquid reservoir with water on top and the manometer liquid in the bottom allows this combination.

The gage glass, part 6, Fig. 3, passes from the bottom of the bi-liquid reservoir either at a slight incline as illustrated or vertically, (the vertical type, using water in the gage glass, has been very satisfactory for all ordinary tests).

By substituting a gage glass of different diameter the magnifying power can be readily changed and the instrument made suitable for various materials or various accuracies desired.

OPERATION

The sequence of operation of the instrument is as follows: The gage board attached to a floor stand is moved to the testing machine and located in a convenient position. The flexible metal tubing permits the actuating part of the instrument to be moved at will. The concrete cylinder is placed on the bed of the machine (or on a movable table adjacent to it) and the clamping rings are set over the cylinder. The set screws of the upper and lower rings are in turn screwed to solid contact with the cylinder. The set screws are then clamped tight in their threads. The spacing bars are loosened and the cylinder with the apparatus attached is set up between the heads of the machine.

The needle valve for the reservoir is now closed and the adjusting piston screwed until the liquid level is at zero on the scale.

Finally the cut out needle valve, part 8, Fig. 3, is closed and the test is ready to proceed.

The above operations require less than ten minutes with an experienced operator.

The initial filling of the instrument requires more time and care, but once it is filled and the gage board is not detached from the actuating bellows it can be used in routine testing indefinitely with consistently accurate results.

The operations described apply to testing of concrete cylinders. The actuating part of the instrument has been used for testing steel, cast iron, and other metals, and for this purpose is made by using the same principle but with smaller clamping rings so as to receive 1⅛" diameter and smaller specimens. It is used with 4 or 8 inch or any gage length by using different lengths of connecting rods, (shown as part 5, Fig. 1,) as the gage length demands These connecting rods can be readily changed.

When making compression tests the zero at the end of the scale nearest the valve body is used and when making tensile tests the liquid zero is at the opposite end and the level approaches the valve body as deformation takes place.

If the gage glass is not long enough to complete the test, the test is interrupted long enough to screw the adjusting piston until the liquid level is returned to zero and the readings are added to the last reading before adjustment. By this method an unusually long test range can be obtained The gage glass, however, is sufficiently long to carry the test well beyond the elastic limit of the material.

RESULTS

Figure 4 shows the results of two tests of concrete cylinders (6" x 12") that were taken with small load increments to show the ability of the instrument to make fine measurements.

Extraordinary care was not used in making these tests; in each case the instrument was set to zero with zero load, which is different from the ordinary method of testing in which the instrument is set to zero at the first increment of load. The readings of the gage

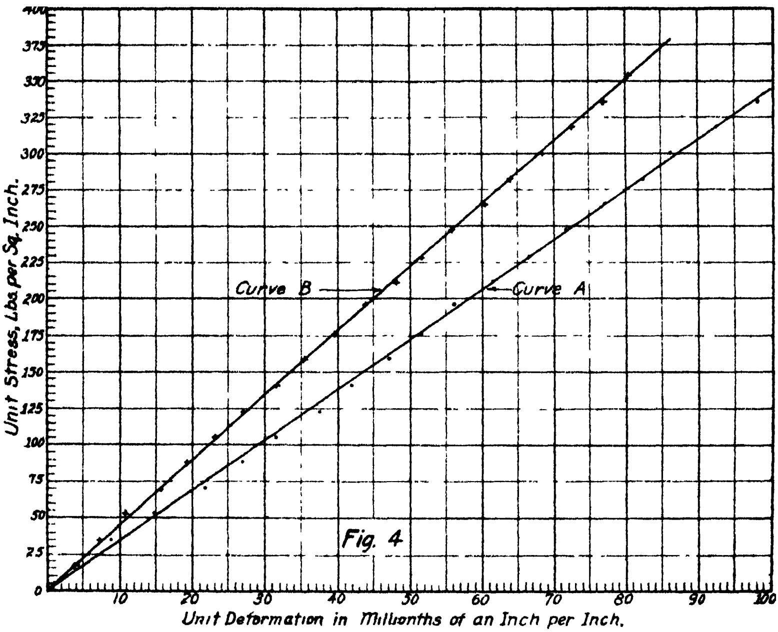


Figure 4. Unit Stress-strain Diagram Showing Results of Compression Tests on Two 6″ x 12″ Concrete Cylinders

glass for test B were made by a different individual than for test A, the latter being entirely without experience in using the instrument.

Curve A shows the beginning of the unit stress-strain diagram for a concrete cylinder having an ultimate unit strength of 1822 pounds. In this case the secant modulus of elacticity at a unit stress of 600 pounds per square inch was 3,280,000 pounds per square inch. Curve B is a similar stress-strain diagram for a concrete cylinder having an ultimate strength of 3700 pounds per square inch and a secant modulus of elasticity at a unit stress of 1270 pounds per square inch, of 4,000,000 pounds per square inch

The testing machine used is considered sensitive to ten pounds at light loads. The swinging of the beam had considerable effect on the reading at any one load value which showed the extreme sensitivity of the instrument. With unit stress increments of only

17.66 pounds per square inch and the variable factors mentioned it is clear that there are several causes providing the variations of points from the mean curves in Figure 4.

Curves obtained from steel and other materials show the same constancy as the ones shown in Figure 4.

FACTORS IN DESIGN

Several problems manifested themselves in the design and in the operation of this instrument and these will be taken up in order.

(1) Magnification.

The magnifying power of the instrument for any given diameter of gage glass can be calculated; however, due to the difficulty in determining the exact working diameter of the bellows and the diameter of the gage glass, the best method of determining the magnifying power is by direct calibration. This can be done by placing the instrument on a known test bar, with a Bureau of Standards certificate, or by determining the movement of the rings of the actuating instrument in respect to each other with a dial indicator. Obviously the latter method is limited by the accuracy of the dial indicator and the set up.

The calculation method of determining the magnifying power will be used to show how the substitutions of different gage glass will give the magnification value desired.

The instrument as illustrated has three bellows with an area of .95 square inches each Assuming a gage glass of 3mm diameter; the bellows have

$3 \times .95 \times 645.2 = 1842$ sq mm. area

The 3 mm gage glass $= 7.069$ sq. mm. area

$$\text{magnifying power} = \frac{1842}{7.069} = 260.5$$

Similarly a 2mm diameter gives 586.0 magnifying power
a 1mm diameter gives 2345.0 magnifying power
and a ½mm diameter gives 9380.0 magnifying power

For convenience a metric scale has been used although other graduations could be employed. Using the mm as the minimum scale

value then 1 mm on the scale with the 3 mm gage glass gives 1/260.5 × 1/25.4 = 1/6,620 or .000152 inch change in length on the **specimen.**

Simarly

1mm on the scale with a 2mm diameter glass gives .0000670 in.
1mm on the scale with a 1mm diameter glass gives .0000167 in.
1mm on the scale with a ½mm diameter glass gives .00000418 in on the specimen.

With a test length of 10 inches the above values become

3mm glass tube; .0000152"/inch. per mm.
2mm glass tube; 00000670"/inch. per mm.
1mm glass tube; .00000167"/inch. per mm.
½mm glass tube; .000000418"/inch. per mm.

The tubes can be interchanged by loosening three screws and a packing gland, the tube drawn out and a new one inserted.

(2) Air Entrainment.

The success of operation of the instrument depends upon the incompressibility of the contained liquid. If air bubbles are caught in the corrugations of the bellows or lodged in other parts of the system the containing liquid becomes compressible and the instrument constant will vary accordingly.

This problem has been satisfactorily met by rapid agitation of the bellows lengthwise during the filling operation and by applying heat to the bellows after filling until steam is produced which will carry away the air

(3) Thermometer Action.

The large volume of liquid in the bellows will expand with changes in room temperature and will cause a rise of liquid in the gage glass. This is partially compensated by the expansion of the copper bellows so that this problem is not so vital as might seem and the instruments so far used in our regular laboratory work have had no further compensation.

The comparatively low thermal expansion coefficient of distilled water along with its chemical inactivity make it a very desirable liquid in the bellows.

The problem can be expressed mathematically as follows:

Let V_c = Volume of the bellows

V_w = Volume of the water

Then $V_c = V_w$ = Volume of the contained water.

Let K_w = Cubical thermal expansion coefficient of water

k_c = Linear thermal expansion coefficient of copper

a = Area of the gage tube

h_{c-w} = Change in height due to expansion in bellows and water respectively.

Then, when

$V_c = V_w$

$\frac{V_w K_w}{a}$ = h_w, the change in height on the gage glass per degree Fahrenheit due to the expansion of the water and the result is positive with increase in temperature.

$\frac{2V_c k_c}{a}$ = h_c, the change in height due to expansion of copper container and the result is negative with temperature rise.

h_t = total change = $\frac{V_w K_w}{a} - \frac{2V_c k_c}{a}$ (The 2 appears on account of the copper bellows being free to expand along two principal axes only.)

$h_t = \frac{V_w}{a}(K_w - 2k_c)$ Equation (1).

Using the instrument as illustrated with three bellows and the 1 mm gage glass:

$V_c = V_w = 2.10 \times 3 = 6.30$ cu. inches. (2.10 = Volume of one bellows determined experimentally.)

K_w (cubical) between 60° and 80° Fahrenheit = .0001245 per degree Fahrenheit.

k_c (linear) = .00000928 per degree Fahrenheit.

a = .785 sq. mm. or 001217 square inches.

Using equation (1)

$$h_t = \frac{6.30}{.001217} (.0001245 - 2 \times .00000928)$$

h_t = .548 inches = 13.92 mm. rise per degree Fahrenheit increase in temperature.

This value seems high but in the actual use of the instrument it is found that trouble from this source has not been so pronounced as might be expected due to the room temperature remaining fairly constant for the period of the test; in fact the great majority of the tests made in the laboratory during the past year have not required temperature corrections Correction can be made easily if desired by reading the change in height on the gage glass each minute for several minutes before and after loading and by noting the minute intervals during the test and correcting the gage reading accordingly. In all cases the instrument is left in the laboratory continuously so that all parts and liquid filler are at room temperature when tests are started.

COMPENSATION FOR TEMPERATURE

It is desirable to eliminate most of the thermometer action when especially accurate work is to be done and a small bore gage glass used. By displacing the water contained in the bellows by a low temperature coefficient substance, a large portion of this expansion effect can be eliminated. Obviously the less water present in the bellows of a given dimension, the less the effect of temperature will be; so by placing a hollow cylinder as a filler inside each bellows and attached to the lower end cap thereof, the expansion effect can be reduced to a very small amount If this filler is made of a material such as Invar, the effect of change of temperature can be eliminated without in any way affecting the operation of the instrument.

If:

k_f = Linear thermal expansion coefficient of filler metal
= 000000662 for Invar per degree Fahrenheit so

V_f = Volume of the fiiller to be placed in the bellows

Then for this case:

$V_w = V_e - V_f$

Then $\frac{(V_c - V_f) K_w}{a} = h_w =$ Expansion of water as registered on gage glass. Result is positive.

and $\frac{3V_f k_f}{a} = h_f =$ Change in height on gage glass. Result is positive.

and $\frac{2V_c k_c}{a} = h_c =$ Change in height on gage glass. Result is negative.

Then $\frac{(V_c - V_f) K_w}{a} + \frac{3V_f k_f}{a} - \frac{2V_c k_c}{a} = h_t$

$V_c (K_w - 2k_c) - V_f(K_w - 3k_f) = ah_t$

Substituting, using $k_f = .000000662$ for Invar

$V_c (.0001059) - V_f (.0001225) = 0$

$V_c = 6.30$ cu. in.

$V_f = \frac{.0006674}{.0001225} = 5.45$ cu in. or 86.3%

In other words 86.3% filling of the bellows with Invar metal is necessary in order that expansion of the water will show no change in height on the gage glass.

Let $V_f = .65\ V_c$ be the practical limit of displacement with a convenient size of bellows

$V_c (.0001059) - .65\ V_c (.0001225) = ha$

$ha = .0000263\ V_c$

$h = .136$ inches

or 3.46 mm on the gage glass per degree Fahrenheit change in temperature. With specimens ten inches long this is equivalent to 00000579 inches per inch of length.

For all laboratory work where greater refinement than this is necessary the connecting rod, part 5, figure 1, can be replaced by a combination of invar and aluminum rods so that no precautions need be taken to avoid temperature effect except at extreme room temperatures.

Complete removal of temperature effect at all temperatures cannot of course be accomplished because of the variable coefficient for water and would be necessary only in the case of long time tests.

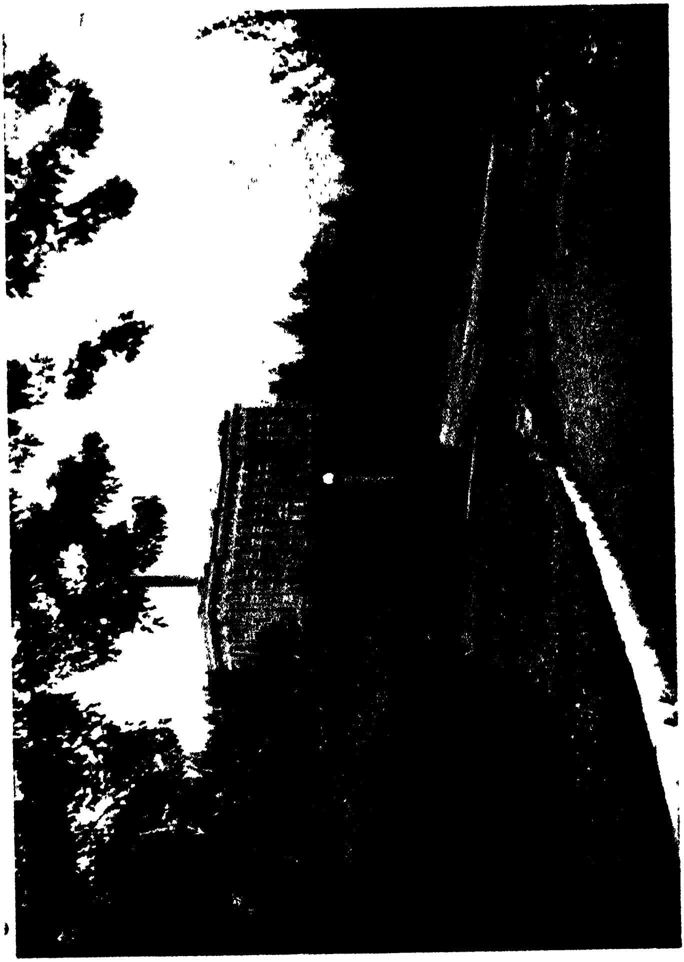
Calculation shows the effect of temperature on the liquid in the copper and glass tubes to be negligible.

CONCLUSIONS

The instrument has been through a development period of nearly two years.

During this time it has been used by the students of engineering in the regular instructional program in common with four other instruments of standard design. It has been found to be convenient and free from annoying uncertainties and takes its place with any of the others as a regular instrument for rapid student or commecrial testing. The author has tabulated the results obtained by these students for the last semester of the college year of 1927-28 and the results obtained with the hydro-static type were very gratifying even though the instrument was undergoing development.

So far as known at the present time, there is no instrument of the hydro-static type that has been applied to the reading of deformations in tensile or compressive tests, and consequently an application for patent has been made



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24. Survey of Fruit Cold Storage Plants. (75c each)
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OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 11 November, 1928 No. 6

A Survey of Fruit Cold Storage Plants in Central Washington

by

H. J. Dana

ENGINEERING BULLETIN NO. 26

ENGINEERING EXPERIMENT STATION

December, 1928

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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A SURVEY OF FRUIT COLD STORAGE PLANTS IN CENTRAL WASHINGTON*

By H. J. Dana

Introduction

The raising and marketing of fruit and of apples especially, is the most important industry of Central Washington, and of certain other sections of the State as well. As is true in any new and rapidly growing industry the lack of well established practice and custom in fruit cold storage has opened the way for a difference of opinion as to what is the best practice or the best and the most economical type of storage for successful fruit handling.

At the urgent request, in 1927, of members of the fruit industry of Washington, the Engineering Experiment Station made a survey of Fruit Packing Plants in Central Washington. At the same time a preliminary survey was made of cold storage plants.† During the summer of 1928 the request was again made for further studies of cold storage plants.

In response to this request, the Engineering Experiment Station in 1928 undertook an "Industrial Efficiency Survey" of some twenty-two Fruit Cold Storage Plants in Washington. In this survey it was attempted to discover the present practice in the industry and wherein the present plants could be operated more efficiently, or could be made to deliver more refrigeration for the same or less power

* The author wishes to acknowledge the very valuable cooperation and assistance, in making this survey, which was given by Mr. Noel Bakke of the Wenatchee-Okanogan Cooperative Federation, and by Mr. L. O. Cockerill and Mr. Curtis Aller, both of the Yakima Fruit Growers' Association.

† See Bulletins No. 23 and 24 listed on page 33 and which contain reports of the 1927 surveys. Bulletin No. 23 is profusely illustrated with drawings.

cost. The following report is written for the information of those who have to do with the owning or operating of fruit cold storage plants, but who do not have the opportunity or the desire to make themselves proficient in the theories of refrigeration. Attempt is made to give comparative data on the different types of plants inspected and to set forth the salient features of each.

Some information is included which will perhaps be of interest to fruit men in other sections of the United States and to others within the State of Washington who contemplate the erection of fruit cold storage plants

Size of Cold Storage Plants

The needs for fruit cold storage are becoming more and more urgent every year so that sizes and capacities of plants are being rapidly increased. At the present time, capacities range on the average from 100 to 300 carloads of boxes—one carload being 756 boxes. However many additions are being made and larger new plants being built every year, showing a tendency toward larger size units. Only one-third to one-half the cold storage plants in each district were included in this survey but those visited were representative in size and type.

The power demand of the refrigerating machinery of a cold storage plant depends upon the size and capacity of the plant. In general the total power demand will probably not exceed 2 H. P. per ton* of refrigeration delivered.

Types of Fruit Cold Storage

There are two general types of fruit cold storage plants in use in Central Washrington; namely, the direct expansion type and the indirect expansion type.

The direct expansion type of refrigeration makes use of ammonia expansion coils located usually on the ceiling of the rooms to be cooled. Such rooms usually are not provided with artificial ventilation or an air circulating system. While there are a few direct

* One ton of refrigeration capacity represents the ability to transfer the amount of heat required to melt one ton of pure ice at 32 degrees F. to water at 32 degrees F. in 24 hours. One ton of refrigeration is equal to 288,000 B. T. U's.

expansion plants for fruit in more or less successful use at the present, the common practice seems to favor the indirect type of refrigeration. The writer knows of at least one such plant which is soon to be converted to the indirect system. Objection to direct expansion systems seems to rest in the fact that there is greater danger of frosted fruit near the ammonia coils, and also that the best apple storage requires a certain amount of artificial circulation of air which the direct expansion system does not provide for

The indirect system of refrigeration is divided into two general types. The older type is known as the dry-air bunker system. The newer type, which is also rapidly gaining favor over the dry-air bunker system is the brine-spray bunker system. It must be recognized that "older" and "newer" are strictly relative terms since the whole fruit refrigeration industry in Washington has been developed largely during the last fifteen years—and most of it during the last six to ten years

Dry-Air Bunker System

A dry-air bunker system provides a separate room or bunker in which all of the ammonia expansion coils are placed. By means of one or more power fans the air is circulated, first through this bunker room and cooled and then through the cold storage rooms where it takes up heat, after which it is again circulated through the bunker room, etc.

Brine-Spray Bunker System

In the brine-spray system the ammonia coils are of the low resistance type and are either submerged in a brine tank or are located just above it. By means of a motor driven pump the brine is forced through a large number of spray heads located above the brine tank. In the case of the exposed coils, this spray impinges upon them and part of it trickles down the pipes to the tank. In the other case the spray drops directly back into the tank. The air to be refrigerated is circulated through the brine spray and is cooled by intimate contact with the finely divided drops of brine. By means of properly shaped baffles, the air as it leaves the brine spray is purged of the brine held in suspension so that it goes to the cold storage rooms free of excess moisture.

Comparative Features

Dry-Air Bunker	Brine Spray
Large bunker space required.	Small bunker space required.
Low suction pressure.	High suction pressure.
Must defrost periodically.	No defrosting of coils.
Frosted coils are inefficient.	Unfrosted coils are most efficient.
Leaking ammonia quickly goes through the storage rooms.	Leaking ammonia absorbed by brine and kept from fruit.
No brine pumps needed.	Must have brine pumps.
No eliminators needed.	Must have eliminators.
No brine to maintain.	Brine must be maintained.
Large amount of ammonia needed.	Smaller amount of ammonia needed.
Less compressor efficiency.	High compressor efficiency.
Larger compressor capacity needed.	Lower compressor capacity needed.

Same fans needed to move the air in either type plant.

Same ducts used to the storage rooms in either type plant.

Approximately same humidities obtainable with either system.

Total H. P. used is approximately the same for both types of plants.

Period of Operation of Cold Storage Plants

In Central Washington, the cold storage season opens in July and August with cherries, peaches, apricots and pears. These are practically all sent to market by September when the apple season begins. Apple storage continues from September through the winter until March and April. Some varieties of apples are placed on the market early in the fall—being held in storage but a few days, while other varieties, coming into storage in the late fall are kept for the spring trade.

From the above, it will be seen that from May to July, or two to two and a half months constitutes an idle period for the fruit cold storage plant.

During the period from July to November, being the warmest part of the storage season, the plant is engaged in receiving packed

fruit at varying degrees of temperature. The refrigerating capacity of the plant carries its peak load during this period owing to the fact that it must cool the warm incoming fruit and supply the building heat leakage losses as well as the losses attending the taking in and shipping out of fruit through open doors. During the winter the refrigeration load is greatly reduced owing to lower outside air temperatures and also because of the fact that the receiving of fruit has ceased. Therefore, it is necessary to design the refrigeration equipment to have sufficient capacity to handle the peak load during the fall season. During the remainder of the season a comparatively small part of the capacity is utilized. To meet these conditions, it is customary to divide the compressor capacity into two or three separate units—usually of different sizes, giving flexibility of control and insuring against a total shut-down in case of trouble with a compressor.

For the storage of apples, it is desirable to maintain the temperature at 30 to 32 degrees F. During the receiving season, it is practically impossible to maintain uniform temperatures day and night. At such times, the temperatures often rise to 34, 36, or 38 degrees in the receiving room during the day time, but are lowered during the night.

Reversing the Air Circulation

In many fruit cold storage plants, where the indirect system of refrigeration is used the cold air is brought to the room to be refrigerated through properly sized ducts, and is discharged into the room through a number of ports located at or near the ceiling. The cold air settles to the floor, allowing the air warmed by the fruit or by building heat leakage to rise to the ceiling and through other ports to enter a set of warm air ducts leading back to the bunker room. It is customary in the designing of many plants to locate the cold air ducts at the ceiling at two opposite sides of the room and the warm air ducts at the ceiling through the center of the room. This causes a circulation of air to take place as shown in Fig. 1. It will be evident that under this system fruit at B and C will be kept cooler than at A. Also, in the attempt to keep fruit at A at the proper temperature there is a chance of frosting fruit at B and C.

Since it is desirable to maintain the temperatures as nearly equal as possible at A, B and C, some plants have been designed so that the air can be reversed periodically—say to be operated for two hours with cold air entering through the two outside ducts and warm air leaving through the center duct. Then for the next two hours, introduce cold air through the center duct, and take out warm air through the two outside ducts. In this way it is contended that danger of frosting is reduced to a minimum and furthermore "warm pockets" are practically eliminated. This is practical especially where the air ports are located in the sides of the ducts as showin in Fig. 1.

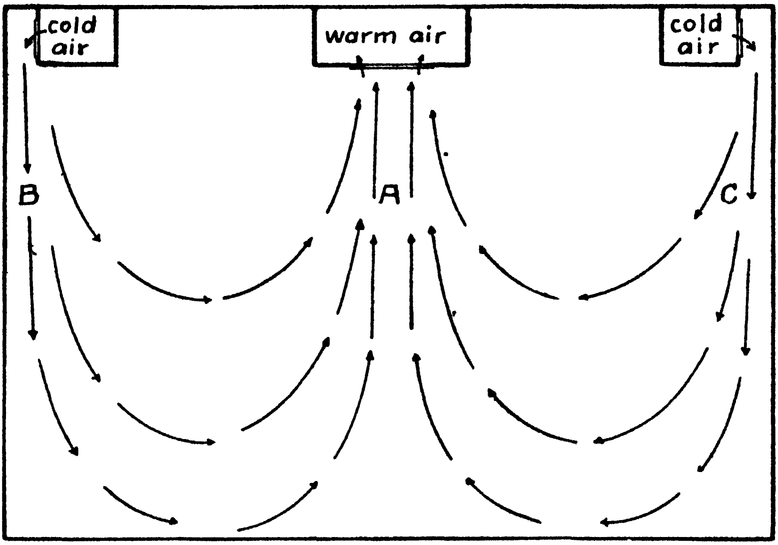

Fig. 1. Showing the customary circulation of air through a cold storage room. The illustration shows an elevation of a cold storage room with the air ducts against the ceiling.

Reversing Mechanism

In order to reverse the circulation of the air through the duct system it is necessary either to reverse the flow of air through the entire system including the fan and bunker room, or by means of cross ducts to switch the warm and cold air ducts leaving the air to flow always in the same direction through the bunker room and fan.

In the first case, by the use of propeller, or ventura type fans, as shown in Fig. 2, the reversal of the fan itself by means of a reversing switch on the motor will accomplish the reversal of the air flow throughout the entire system.

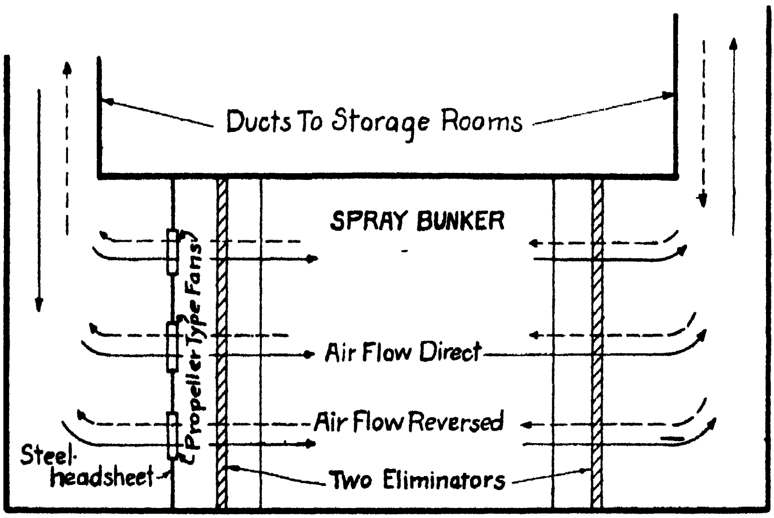

Fig. 2. Reversing the air flow through cold storage rooms by means of reversible fans. Ground plan of bunker room and ducts to cold storage rooms.

In the second case, by the use of special cross ducts and dampers the flow of air can be reversed in the ducts to and from the rooms while continuing in the same direction through the bunker room and fan as in Fig. 3.

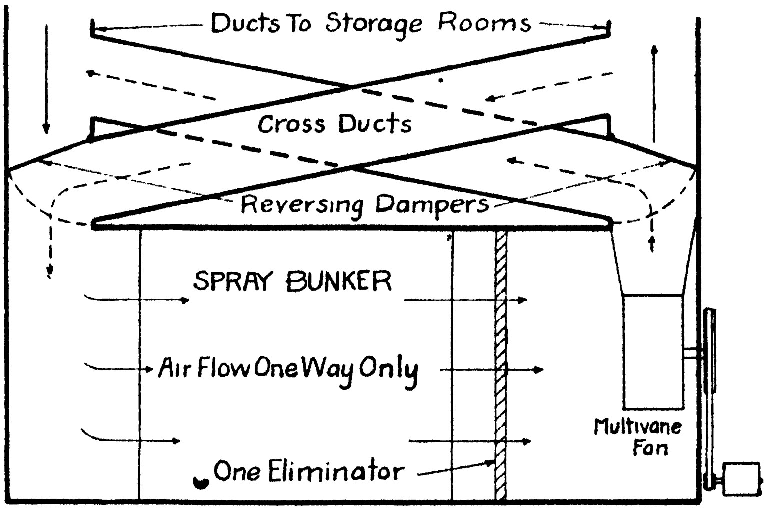

Fig. 3. Reversing the air flow through cold storage rooms by means of cross ducts and dampers. Ground plan of bunker room and ducts to cold storage rooms.

The propeller type fan lends itself to easy reversal by reversing switches on the motor. However, because of the necessary design of its blades it will not move as much air in reverse as in direct. It is also very inefficient in delivering air against the usual back pressures encountered in cold storage practice. On the other hand while the multi-blade type fan cannot be reversed, it is far more efficient in the quantity of air handled per H. P. used. The comparative features of the two systems are cited below.

Comparative Features of Two Air Reversing Systems

Propeller Type Fans	Multiblade Type Fans
Low horse power efficiency with consequent heating of the air by churning.	High horse power efficiency with consequent minimum heating of the air.
Consequent high power bills.	Consequent low power bills.
Two or more units give flexibility.	One unit gives no flexibility except by changing pulley sizes.
High first cost of system.	Lower first cost of system.
Minimum of space required for fans.	Cross ducts and fan require additional space
Easily reversed by changing switches.	Reversal requires manual operation of dampers in both ducts.
Lower air volume on reversal than on direct with attendant warming of the house.	Practically no difference in air volume in direct or reverse, with house temperature kept constant.
Multiple units guarantee against absolute break down.	Break down puts entire air system out of commission.
Motor power heat losses discount several tons of refrigerating capacity.	Motor power heat losses discount minimum of refrigerating capacity.

Additional Points of Comparison for Brine Spray Systems

Propeller Type Fans	Multiblade Type Fans
Requires two expensive eliminators.	Requires only one eliminator.
Extra eliminator increases friction and static head of system.	Minimum of friction or static head in system, with consequent minimum of heating of air and minimum of fan H. P. required.

Fan Efficiencies

Where an indirect system of refrigeration is employed, it is necessary to use a power fan to accomplish the required circulation of the refrigerated air. It is customary to design an air system for this purpose on the basis of approximately 1000 C. F. M. (cubic feet per minute) of air per ton of refrigerating capacity. The average size plants, therefore, in use in Central Washington will require from 30,000 to 60,000 C. F. M. of air to be handled by the fan. The static pressure under which most of the installations surveyed were found to operate was ½" to ⅝" water pressure. Under these conditions the most economical fan to use is the multivane, or "sorocco" type, of which there are several good, and well-known makes These fans are carefully designed to move the greatest quantity of air with the least friction and churning and consequently with the smallest possible power demand.

However, it is very important, in the interest of economy of operation, that the correct size fan be chosen for a given installation For instance, in a certain plant, a small size and efficient fan of modern make, operating at high speed delivered 25,000 C F. M. of air against ⅝" W. P. and required 18 H. P. delivered to the motor. With the proper size fan, the same amount of air could be delivered at the same pressure with a power demand of 6½ H. P. This indicates that 11½ H. P. have been wasted in churning the refrigerated air, which in turn results in heating the air. The power schedules in Central Washington are such that the average cold storage company will pay approximately $5.00 per H. P. per month for power. At this

rate the correct size fan in the above instance would effect a monthly saving of $57.50 in power cost.

In addition to the power bill saved, the larger size fan saves 11½ H. P. of heat from being put into the refrigerated air as compared with the smaller fan. Each H. P. of heat represents .213 tons of refrigeration, or 2.45 tons of refrigeration was required in the above instance to overcome the unnecessary 11½ H. P. used by the smaller fan. This means the cold storage rooms in that plant got 2.45 tons less of refrigeration than the capacity of the engine room with the result that the fruit temperatures could not be so well controlled.

Furthermore, the use of the small size fan not only results in a practically idle, or "dead", investment of 2.45 tons of refrigerating capacity, averaging perhaps $400 per ton investment but it requires an additional power bill of approximately $18.00 per month to operate this "dead" investment.

Briefly then, the undersize fan will:

1. Unduly heat the refrigerated air.
2. Cause an excessive fan power bill.
3. Absorb refrigerating capacity of the compressors.
4. Give no returns for power cost to operate this "dead" investment.

Propeller type fans while very efficient in moving air at very low back pressures, should be considered in the class with undersize fans discussed above when working at the static pressures found in refrigerating practice, namely, ⅜" to ⅝" of water pressure

Cold Storage Building Construction

The function of a cold storage building, aside from providing sheltered storage space, is to prevent the flow of heat from an outside source to the commodity to be stored. To accomplish this object, use is made of some type of building material which is a poor conductor of heat.

The structural part of the usual cold storage building may be of wood, stone, brick, tile or concrete, or a combination of any or all of the above. Most of the cold storage plants in Central Washing-

ton are constructed either of brick, of brick and hollow tile, or of concrete. In most brick or hollow tile buildings, concrete is used also as the foundation material. Brick and hollow tile and concrete, while serving as excellent building materials, are also comparatively good conductors of heat, and therefore are not suitable alone as insulators against the flow of heat into the cold storage space. To provide the necessary heat insulation on the walls and floor and ceiling of a cold storage plant, an added thickness of good heat insulation is usually provided.

Among other things, the virtue of a good heat insulator for cold storage lies in its ability to entrap very small bodies of air, the latter in finely separated form being recognized as one of the most efficient heat insulators in use. For this reason large air spaces in partitions do not serve as well as if these spaces were packed with some material which entraps the air in finely divided portions.

There are several insulating materials commonly used in cold storage plants in Central Washington. The most efficient, and at the same time the most expensive material used is corkboard. The next most commonly used material is planer shavings.

In Table I. is shown the comparative heat loss through various insulating materials used in cold storage buildings.* The heat loss is in British Thermal Units per hour per square foot of material one inch thick and at a difference of temperature of one degree Fahrenheit between the two sides.

Table I.

Material	Heat Flow B. T. U. per hr. per sq. ft. per degree
Air—no circulation	.167
Corkboard	0.317
Wood	1.000
Brick	4.000
Concrete	8.300
Planer shavings	0.420
Air space in partions	1.000 to 1.700

* Data taken from Handbook of Refrigeration, by H. J. Macintire.

Relative Humidity

The term relative humidity is intended to designate the percentage of moisture by weight which the air contains as compared to the maximum weight of moisture which the same air at the same temperature could carry without precipitating. This capacity of air to hold moisture increases with increase of temperature. In fruit cold storage plants it is conceded that 85% relative humidity in most cases is most desirable for the proper preservation of fruit. Higher humidities tend to promote diseases of the fruit while lower humidities tend to draw moisture out of the fruit and thereby cause undue shrinkage.

There is considerable misunderstanding as to how the relative humidity of the cold storage room may vary under different operating conditions. For instance, a cold storage room which has been closed for two or three days and the temperature of which has reached a stable low value may show a relative humidity of 84% to 86%. If a quantity of warm fruit were to be introduced into this storage room the temperature of the air in the room would probably rise several degrees. At the same time the relative humidity of the air would materially decrease in value even though the total moisture content were the same. This would arise from the fact that the warmer air is capable of sustaining a larger total amount of water.

It will be seen from the above that the relative humidity as shown by a test in a cold storage room early in the morning may be 85%. Later in the day after the doors have been open to receive warm fruit the relative humidity may decrease to 50% or 60%. Therefore, a test of relative humidity at some certain time of the day may be no indication of the average condition which exists over the twenty-four hours. For this reason tests of relative humidity during the daytime of the receiving season do not necessarily convey any very definite information. After the storage room has been filled and temepratures are brought down tests of humidity will then serve to indicate perhaps for days at a time the condition of the air under which the plant is operating.

During the time this survey was being made all plants were engaged in receiving and shipping fruit. For this reason, and as stated

above, a test of humidities during the day at that time would not serve to indicate a true operating condition of the plant, and at best might indicate only a comparative condition of operation as between plants. Tests of humidities were made in most of the plants visited and were made at some time between the hours of 10 A. M. and 5 P. M. In these tests the minimum humidity found in any plant was 63% and the maximum was 84½%. The usual humidities ranged from 72% to 78%. Furthermore there seemed to be no difference between the humidities found in brine-spray plants as compared to dry-air bunker systems.

Relative humidity may be greatly influenced by the method of operation of a plant. For instance, the operation of the bunker at a very low temperature will freeze a larger amount of moisture out of the air, depositing it on the ammonia coils as frost, or as in the brine spray plant, this moisture accumulates in the brine and periodically must be drawn off. In this case the plant would probably be operating with a comparatively small amount of comparatively cold air and the relative humidity in the storage room would be low. The use of a larger amount of warmer air through the bunker makes possible the maintaining of a higher relative humidity in the storage room.

Testing Humidities

To test relative humidity use is made of two thermometers. One is known as a "dry bulb" and the other as a "wet bulb" thermometer. The former may be any good thermometer while the latter may be of the same make and type except that the mercury bulb is encased in a piece of thin muslin. These two thermometers are usually attached to a frame provided with a handle about which they are free to rotate. This is known as a "sling psychrometer". To operate a sling psychrometer, the muslin on the wet bulb thermometer is moistened, usually by dipping the bulb with its muslin jacket into water. Then the two thermometers are swung about the handle until the temperature indicated by each has ceased to change. It usually requires several minutes swinging to accomplish this. By means of these two temperature readings the relative humidity can then be determined from a set of relative humidity tables or a psychrometric

chart. Too brief "swinging" or too dry muslin on the "wet bulb" will indicate a higher relative humidity than actually exists.

In testing relative humidities in a cold storage plant, the use of a sling psychrometer which has been kept in a warm engine room will necessitate an exceptionally long first operation to remove the engine room heat before the temperature shown by the thermometers will indicate the correct temperatures. For this reason, it is recommended, either that the sling psychrometer be kept in the cold storage room, or that it be placed in the cold storage room some quarter or half hour before being used.

The stationary type of psychrometer is not considered reliable for use in a cold storage plant. To be accurate it must operate under more or less ideal conditions as to cleanliness and water supply, and these conditions are scarcely attainable in the average plant.

Table II.

1	2	3	4	5	6	7	8	9	10	11
Plant Number	Cubical Contents of plant, Cubic Feet.	Storage capacity in boxes. 2.7 cu. ft. per box.	Outside exposure in square feet	Estimated Heat leakage from bldg in tons of refrigeration	Type of refrigeration	Size of pipe in bunker coils.	Length of ammonia coils in bunker.	Square feet of surface of ammonia pipe in bunker.	Suction pressure at compressor	Head pressure at compressor.
1	344,000	127,400	43,424	9.98	Dry Air	2"	13,600	8,450	23	140
2	323,200	120,000	43.000	9.89	Dry Air	2"	14,400	8,950	18	137
3	402,500	149,000	48,900	11.24	Dry Air	2"	18,020	11,200	26	157
4	204,800	75,000	25,500	5.86	Dry Air	2"	12,800	7,960	24	146
5	171,900	63,000	28,720	6.60	Br. Sp. Trickle	......	....	....	24	146
6	279,600	103,000	44,000	10.12	Dry Air	2"	10,400	6,470	21	134
7	282,000	104,000	31,900	7.33	Br. Sp. Trickle	1¼"	1,728	750	....	......
8	540,000	200 000	51,400	11.82	Dry Air	2"	15,200	9,450	24	152
9	586,000	217,000	58,000	13.34	Br. Sp. Trickle	1¼"	1,600	696	24	152
10	132,000	49,000	17,300	3.97	Dry Air	2"	7,000	4,350	10	140
11	560,000	214,000	51,000	11.73	Dry Air	2"	15,700	9,760	18	140
12	1,988,387	740,000	111,000	25.53	Br. Sp. Subm.	......	....	....	30	165
13	456,000	168 000	40,300	9.27	Br. Sp. Trickle	1¼"	3,600	1,565	27	115
14	214,000	79,000	36,350	8.36	Dry Air	2"	10,080	6,269	20	128
15	201,600	74,000	38,300	8.80	Direct	2"	7,920	4,920	8	110
16	601,900	224,000	58.400	13.43	Br. Sp. Subm.	1¼"	9,400	4,085	32	140
17	635,000	235.000	58 400	13.43	Br. Sp. Subm.	1¼"	9,400	4,085	30	120
18	321,500	119,000	34.800	8 00	Br. Sp. Subm.	1¼"	5,800	2,520	32	130
19	250 000	93 000	30.400	6.99	Br. Sp. Subm.	1¼"	6,300	2,740	29	125
20	668,500	247,000	69,000	15.87	Br. Sp. Subm.	1¼"	6,500	2,852	13	135
21	237,500	68,000	34,100	7.84	Dry Air	2"	4,200	2,620	28	135
22	387,000	142,000	42,200	9.70	Br. Sp. Trickle	1¼"	1,440	626	14	120

Table III.

1	12	13	14	15	16	17	18	19	20	21	22
Plant Number	Number of Fans Used.	Type Fans Used.	Total Fan Horse Power.	Capacity of air system, C. F. M.	Horse Power of fans used, per 1000 C.F.M	Static Pressure at fan in inches of water.	Air changes per hour Empty house.	Air temperatures into bunker.	Air temperatures out of bunker.	Temperature drop through bunker.	Temperature of the ammonia (approx.)
1	2	multivane	32.70	47,000	.695	1¾"	8.2	36.5	31.5	5.00	9
2	1	multivane	22 40	58,800	.381	⅝"	10 9	32.	26.6	5.4	3
3	2	multivane	18.75	38 200	.491	½"	5.7	36.	28.	8.0	12
4	1	multivane	10.00	25,000	.400	½"	7.4	33.3	27.5	5.8	10
5	1	multivane	5.00	11,000	.227	⅝"	3.9	33.	25.	8.	10
6	1	multivane	18.00	25,100	.716	⅞"	5.4	40.1	29.3	10.8	7
7	1	multivane	10.5	45.000	.187	½"	9.5	32.	25.0	7.0	.....
8	1	multivane	20.6	46,000	.448	1 "	5.1	34.5	25.	9.5	10
9	1	multivane	6.00	45 000	.133	⅜"	4.6	36.	28.	8.0	10
10	1	multivane	5.05	15 000	.336	¾"	6 8	36.5	25.7	10.8	— 8
11	2	multivane	31.30	27.000	1.160	1⅛"	2 9	38.3	20.3	18.3	3
12	2	multivane	....	160 000	....	....	4.8	......	......	......	16
13	1	multivane	....	68 000	....	⅜"	8.9	......	......	......	13
14	1	multivane	12.00	21,800	.550	⅜"	6.1	41.	33.	8.0	5
15	0	....	....	....	....	....	....	35.	30.	5.0	—12
16	3	propeller	25 32	52,000	.478	⅝"	5.2	35.	27.	8.0	18
17	3	propeller	16.57	....	....	⅝"	....	33.	24.	9.0	16
18	2	propeller	8.95	....	....	⅝"	....	36.	27.75	8.25	18
19	2	propeller	12 06	32,400	.373	11/16"	7.8	33.	27.	6 00	15
20	2	propeller	13.3	50,000	.266	⅝"	4.5	33.	22.	11.00	— 4
21	1	multivane	6.3	22 000	.286	⅝"	5.6	35.	29.	6.0	14
22	1	multivane	9.0	48,000	.187	½"	7.5	34.	32.	2.0	— 3

Data on Cold Storage Plants

While surveying the twenty-two different cold storage plants, comparative data were secured which may be of interest to those concerned with the building and operation of such plants. Those whose plants were included in this survey may also be interested to see how their plants compare with others in certain characteristics.

In Table II. is shown the size and storage capacity of each storage plant, together with the type of refrigeration employed and some of the data relative to the refrigerating equipment, while in Table III. is shown the data pertaining more particularly to the air systems of the different plants. For easy reference, the columns are numbered consecutively

Storage Capacity

Column No. 1 shows arbitrary numbers assigned to the different plants included in the survey. Column No. 2 shows the cubical capacity of the plant building from which in column No. 3 is calculated the approximate storage capacity of the plant. The figure of 2.7 cubic feet per box is based on a study of the practice of stacking fruit boxes in storage, and is considered ample to include the storage space occupied by boxes, by necessary aisles, by air ducts and by elevators and conveyors. This column could be converted into carload capacity by dividing the items by 756—the number of boxes per carload.

Heat Leakage Load

After the close of the receiving season and when the doors and openings are all closed, the refrigeration load of a cold storage plant consists principally of leakage of heat through the outside walls of the building and of mechanical heat from motors, lights, workmen, etc. Therefore, it is desirable as far as refrigeration load is concerned to build a cold storage plant with the smallest possible amount of outside surface. Theoretically, a sphere would have the smallest possible exposed surface for a given cubical content. In practice, the square building would be the nearest approach possible and should be designed to be nearly as tall as its horizontal dimension. Local circumstances and other considerations often make it desirable to ignore the

above in favor of a long narrow building, or a building with greater horizontal than vertical dimensions.

Some of the items effecting heat leakage through the walls of a cold storage plant are, thickness of the wall, material in the wall, kind and thickness of insulation, temperature difference between inside and outside surface, character of the inside and outside surface as regards smoothness and color, wind velocity outside the building, etc. It is apparent that all of these items could be properly evaluated for a given plant only with the greatest difficulty. From practice and experiment it has been learned that the maximum heat leakage through the walls, ceiling and floor of the average cold storage plant, including leakage through openings will not exceed 2 B. T. U.* per square foot of outside surface per twenty-four hours per degree temperature difference between the inside and the outside air. It often is much less than 2 B. T. U. but, for purposes of ascertaining the probable maximum heat leakage from the average well insulated cold storage plant, it is customary to use this figure. From Column 4 which represents the outside exposure of walls, ceiling and floor of each plant, is derived the estimated heat leakage per twenty-four hours based on an inside temperature of 32 degrees and an outside average temperature of 65 degrees Fahrenheit. Dividing the total heat leakage of the building in B. T. U. by 288,000 (which represents the B. T. U. required to produce one ton of refrigeration per 24 hours) gives the estimated leakage load of the building in tons of refrigeration, column 5, and represents the amount of compressor capacity required to handle the item of heat leakage alone

Type of Refrigeration

The type of refrigeration employed in each plant is set forth in column 6. These are: the dry-air bunker system with the ammonia coils located in a small bunker room, the brine-spray system with the ammonia coils submerged in a brine tank, the brine-spray system with the ammonia coils exposed to the brine spray which latter trickles down the coils and into the brine tank, and the direct sys-

* A British Thermal Unit is the amount of heat required to raise the temperature of one lb. of water one degree Fahrenheit.

tem in which the ammonia coils are located in the room to be refrigerated. In many of the plants using the indirect system, use is made in one or more rooms of direct expansion coils also, giving a combination system for quickly refrigerating pears and other fruit requiring to be cooled very rapidly.

From columns 7 and 8 is obtained the data in column 9, namely, the square feet of ammonia pipe surface in the bunker room. In several plants, as mentioned above, additional refrigerating surface is also used in some of the refrigerated rooms and is not included in column 9.

In the dry air bunker system, the heat in the circulated air will pass through a clean pipe into the ammonia gas at the rate of approximately 3 B. T. U. per hour per square foot of pipe surface per degree of difference between the temperature of the air and the temperature of the ammonia. When the pipe becomes frosted, this transmission becomes materially reduced because of the fact that ice, and particularly frost, is a relatively good heat insulator. According to the information available the heat conductivity of the frost on the ammonia coils is only one-twentieth to one-thirtieth as high as through the clean pipe. From this it will be evident that frost on the bunker coils is very similar to a big fur overcoat—it effectively retards the passage of heat from the air through the pipe to the ammonia.

In the light of the above, it is apparent that it is highly desirable to operate the ammonia coils with just as little frost on them as possible—otherwise, they will deliver less than rated capacity and the power bill on the compressors per ton of delivered refrigeration will be higher. In this connection, the brine spray system lends itself to higher efficiency operation since the brine serves to keep the ammonia coils perpetually free from ice. Furthermore, it is possible to realize a much higher rate of heat transmission from the air through the brine and through the pipe to the ammonia, partly because of the intimate contact between the brine and the air, and partly because of the higher transmission possible through wet contact of the brine with the pipe instead of the dry contact of the air with the pipe. For this reason, it will be noted that brine-spray plants

use only one fourth to one third the square feet of ammonia pipe surface needed by an equivalent dry-air system. This permits the use of a comparatively smaller bunker room for the brine-spray system.

Suction Pressure and Operating Efficiency

As noted above, heat will flow far more readily from air to ammonia through the walls of a clean pipe than through one coated with frost. In other words, with a coat of frost on an ammonia pipe, the ammonia must be considerably colder in order to secure a larger temperature difference between it and the air and thereby accomplish the transfer of the same amount of heat, or to deliver the same tons of refrigeration. In order to lower the temperature of the ammonia it is necessary to adjust the refrigerating system so as to lower the suction pressure on the compressors. In column 10 is shown the suction pressures noted on the gauges of the different plants at the time they were visited. It will be understood that these are not necessarily the average nor the usual suction pressures in all cases since the suction pressure at a certain time in a given plant will depend somewhat upon the load on that plant at that time. However, it will be noted that the brine spray plants as a rule operate with a higher suction pressure than do the dry air bunker systems and this is to be expected for the reasons cited above.

Refrigerating systems are based upon the fact that it takes some certain amount of heat to change a liquid into a gas at the same temperature. This is known as the latent heat of vaporization and for a given liquid, such as ammonia, varies only slightly with changes in pressure. The function of the compressor is to pump away the ammonia gas as fast as it is formed in the ammonia coils. The higher the suction pressure of this gas, the more weight of gas will be handled per stroke of the compressor. In other words, the higher the suction pressure, the fewer strokes of the compressor will be necessary to handle a given weight of ammonia. The total power consumption per pound of ammonia pumped is also less at the higher suction pressure, because of the fewer strokes required, resulting in lower power cost per ton of refrigeration delivered. It also follows that the higher the suction pressure, the smaller will be the compres-

sor capacity required to deliver a given amount of refrigeration. Here again, the brine spray plant makes possible an economy in first cost of compressor equipment.

Discharge Pressure

In column 11 is given the head pressure, or discharge pressure of the compressors at each plant visited. There is a peculiar significance attached to the value of this discharge pressure. The work of compressing the ammonia gas results in increasing its temperature and the higher the temperature, the higher the pressure required before the gas will liquify. The higher the discharge pressure, the more power will be required to operate the compressor. Therefore, the higher the condenser temperature, the greater will be the power cost of the plant.

The function of the ammonia condenser is to extract heat from the hot compressed gas and permit it to liquify, and to further reduce the temperature of the liquid ammonia. Ammonia condensers most commonly used may be of the double pipe type, the shell and tube type or the flooded type. Among the factors which may contribute to high discharge pressure are: too small condenser capacity, too small amount of condenser water, and the use of warm condenser water. It is evident, therefore, in the interests of power economy, that it is necessary to provide ample condenser capacity measured in terms of surface area, and plenty of cold water through the condenser—the colder the better.

The Air System

Table III. contains information relative to the air systems of the plants visited. In columns 12 and 13 are given the number and type of fans used. In column 14 is shown the horse power used by the fans in each plant to deliver the cubic feet of air per minute shown in column 15. Of particular interest is the information relative to the power used per thousand cubic feet of air delivered per minute, as shown in column 16. All of those plants which require more than .500 H. P. per 1000 C. F. M. were found to be operating with too small a fan, air ducts too small or poorly designed, or a

combination of the above, which results also in unduly heating the air, thereby discounting a certain amount of compressor capacity.

Those plants operating with a fan power demand of less than .200 H. P. per 1000 C. F. M. give evidence of being well designed as regards adequate size fan and properly designed ducts. Such plants are securing a maximum of refrigerating service at a minimum of operating cost.

Static Pressure

In the design of an air duct system for a cold storage plant it is important that the ducts be large enough to convey the required air at a velocity not exceeding 1000 F. P. M. (feet per minute). At a higher velocity the heating of the air due to friction against the walls of the ducts, etc., becomes excessive, and in refrigeration work it is desirable to heat the air as little as possible. Air friction depends upon the velocity of the air through the ducts, the smoothness or roughness of the inside of the ducts, and the pressure or absence of swirls and eddies in flowing air. For instance, a smooth curved elbow will change the direction of the air with a minimum of disturbance to the air stream, while a square turn will cause eddies and churning of the air which results in friction and heat By means of comparative tests it has been found that the loss due to a square turn in a rectangular duct is as much as eight times the loss which would take place if a properly curved elbow were used. All friction in a duct system is measurable in terms of static pressure, which is the pressure tending to burst the walls of the duct. The lower the static pressure of the system the less power will be required on the fan to deliver a given quantity of air per minute. Therefore, it is desirable to have a static pressure as low as possible both on account of economy of fan power and on account of heating the refrigerated air

Measuring Static Pressure

In column 17 is given the static pressure measured in each plant This was measured at the fan by means of a glass "U" tube as follows: a small copper tube was inserted through the wall of the fan discharge duct to extend nearly to the center of the duct as shown in Fig. 4. By means of a flexible rubber hose, this tube was connected

to one end of the glass "U" tube which was partly filled with water. The other end of the "U" tube was open and exposed to the same air pressure as the inlet to the fan, being in most cases but a few feet from the fan inlet. In this way one end of the "U" tube was exposed to the air pressure entering the fan and the other end was

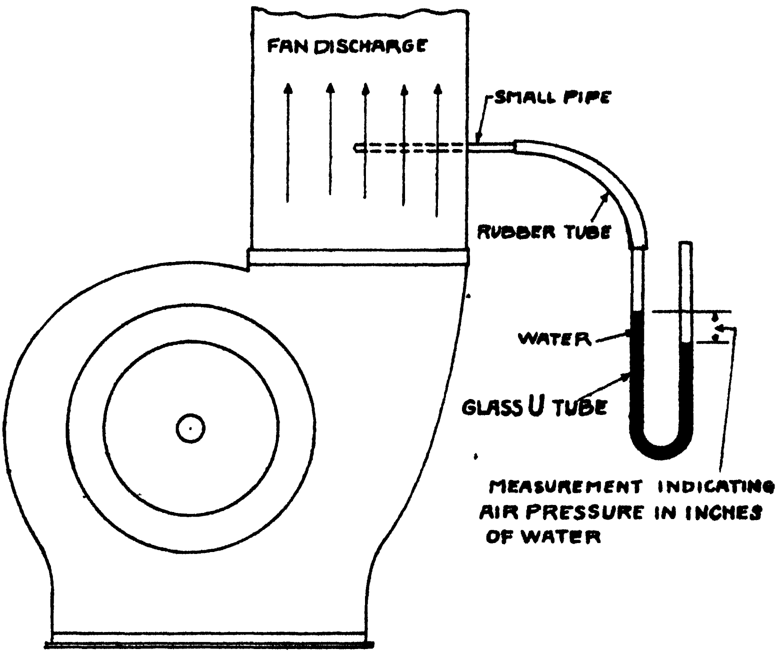

Fig. 4. Method of measuring the static pressure of an air system.

exposed to the air pressure leaving the fan—giving the pressure developed by the fan. Care was taken that the mouth of the copper pipe in the air stream was not pointed either toward, or away from the air flow. Pressure was measured in inches by measuring the difference in water level in the two sides of the "U" tube.

Reducing the Fan Speed

A well designed air system in a cold storage plant will operate at a static pressure of from ½" to ⅝" of water. The closing of the air ports during the late part of the season when a smaller quantity

of air is needed, will cause the static pressure to increase. In many cases, a substantial economy in fan power could be effected by using a smaller motor pulley in the late season, thus decreasing the fan speed. This would result in delivering a smaller quantity of air with open ports—thus keeping down the friction and the static pressure and saving money for fan power. For instance, a certain fan running at 175 R. P. M. will deliver 50,000 C. F. M. of air to a plant at ⅝" static pressure with a power demand of 15¼ H. P. By decreasing the speed of the fan to 140 R. P. M. it will deliver 40,000 C. F. M. with a power demand of approximately 8¾ H. P., showing a monthly saving in the power bill of $32.50. In this case, reducing the speed of the fan and, with the airports in the duct system undisturbed, the static pressure will reduce to a little over ⅜".

Comparative Air Capacity

On the basis that all the storage rooms in a plant were empty and that the air system were operating at full capacity, it is apparent that the circulating fan would handle an equivalent of all the air in the plant a certain number of times each hour. From the size plant given in column 2 and the air delivered as in column 15 was computed for each plant the number of times per hour the air would be completely changed if the storage rooms were entirely empty of fruit. This offers a certain basis for comparison between plants as regards the relation between air supply and cubical contents of the building. From five to eight changes per hour was found to be most common. However, in the case of plant No. 11, it is clearly an instance of operating with too small a supply of air. It will be understood that this data is merely given as a basis for comparison and not as a basis for plant design.

The temperature of the air leaving the storage rooms and entering the bunker room is shown in column 19. In column 20 is shown the temperature of the refrigerated air as it leaves the bunker on its return to the storage rooms. The temperature drop through the bunker is shown in column 21. It will be recognized that the lower the temperature of the outgoing air, the more moisture has been "frozen" out of it in its passage through the bunker, and the lower will be the relative humidity possible to maintain in the storage

rooms. Where a high relative humidity is desired, it is recommended to use a larger volume of air with a consequent higher outgoing temperature and a lower temperature drop through the bunker.

In column 22 is shown the ammonia temperatures corresponding to the suction pressures shown in column 10. Take for comparison, plant No. 19 and plant No. 30. The suction pressures are 29 and 13 lbs. with temperatures of 15 and —4 degrees Fahrenheit, respectively. It will be noted that the square feet surface of ammonia pipe in the bunker is nearly the same in each plant, while the relative size of the plants is approximately one to two and a half. In spite of the fact that plant No. 20 has some direct expansion in part of the storage, it is apparent that the refrigeration load of the plant is overtaxing the bunker capacity, especially as regards the amount of air being cooled. Such a large temperature drop necessitates a low ammonia temperature with consequent inefficient operation of the compressors at a low suction pressure. Such a plant would benefit from an increased air supply through an enlarged bunker capacity.

SUMMARY

Fruit Cold Storage is comparatively new in the Pacific Northwest and is developing so rapidly that practice is not yet standardized.
rooms. Where a high relative humidity is desired, it is recommended to use a larger volume of air with a consequent higher outgoing temperature and a lower temperature drop through the bunker.

Cold Storage plants range in size from 100 to 300 carload capacity on the average, and employ the direct expansion, or the indirect expansion system of refrigeration, or a combination of both.

In the indirect expansion system, which is fast replacing the direct expansion system, the brine-spray type is growing in popularity. It requires less space, is more economical to operate, and the first cost is less than the dry-air bunker system.

The Cold Storage season is not continuous throughout the year and the maximum demand for refrigeration extends over a period of only two or three months.

The design of an air handling system involves questions of size and capacity, and economy of operation. Many plants now in operation could effectively increase their capacity and decrease their costs of operation by replacing some of their present fans and ducts, the cost of which would be returned by decreased power bills.

Cold storage plants in the Pacific Northwest, are, for the most part, built of brick and concrete and insulated with corkboard or planer shavings.

Relative humidity depends upon a number of operating conditions and may be controlled to a certain extent. Care is required in making tests of relative humidity to insure accurate results.

Comparative data on different plants indicates that some are well designed and operating efficiently while others are handicapped by some one or more features which are incorrectly proportioned to the load on the plant The most common fault is inadequate air supply or undersize fans and ducts. Other features of a cold storage plant merit close comparative study in order to realize the highest operating efficiency.

Engineering Bulletins

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1. Sewage Disposal for the Country Home. (Out of Print.) By O. L. Waller and M. K. Snyder, March, 1914, July, 1916.
2. How to Measure Water. By O. L. Waller, October, 1915, Reprint 1925 (Revised and Reprinted as part of Engineering Bulletin No. 20.)
3. Water Supply for the Country Home. (Out of Print.) By M. K. Snyder. See Eng'rg. Bul. No's. 9, 10, and 11.
4. Construction and Maintenance of Earth Roads. By L. V. Edwards, April, 1916.
5. Cost of Pumping Water. Reprinted as Extension Bul. No. 103. By O. L. Waller, August, 1916.
6. Fuel Economy in Domestic Heating and Cooking. By B. L. Steele, December, 1917.
7. Thawing Frozen Water Pipes Electrically. By H. J. Dana, October, 1921.
8. Use of Ropes and Tackle, Illustrated. By H. J. Dana and W. A. Pearl, December, 1921.
9. Well and Spring Protection. By M. K. Snyder, July, 1922.
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18. Relation of Road Surface to Automobile Tire Wear. Third Progress Report. By H. J. Dana, October, 1926.
19. Rhythmic Corrugations in Highways. By H. V. Carpenter and H. J. Dana. February, 1927.
20. How to Measure and Use Water for Irrigation. By O. L. Waller, March, 1927.

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22. Spray Residue and Its Removal From Apples.
By F. D. Heald, J. R. Neller and F. L. Overley of the Agricultural Experiment Station in Cooperation with H. J. Dana.

23. Survey of Fruit Packing Plants. ($2.00 each)
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24. Survey of Fruit Cold Storage Plants. (75c each)
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25. An Extensometer and Compressometer of the Hydro-static Type.
By H. H. Langdon, October, 1928.

26. A Survey of Fruit Cold Storage Plants in Central Washington. By H. J. Dana, December, 1928.

27. The Automatic Underfeed Coal Stoker for Domestic Heating. By H. J. Dana.

View of the east entrance of the Administration Building.

The Mechanic Arts Building, occupied by the College of Engineering.

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 11 December, 1928 No. 7

FIRST PROGRESS REPORT

Second Edition, Revised

The Automatic Underfeed Coal Stoker for Domestic Heating

by

Homer J. Dana

ENGINEERING BULLETIN NO. 27

ENGINEERING EXPERIMENT STATION

October, 1929

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st. 1911 This was followed by later appropriations. In April, 1919, this department was officially designated, 'Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washintgon The work of the station is made available to the public through technical reports, popular bulletins, and public service The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Published bulletins are available as listed on pages 18 and 19.

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A winter scene on the State College Campus

THE AUTOMATIC UNDERFEED COAL STOKER FOR DOMESTIC HEATING

By Homer J. Dana*

Modern demands for healthful living conditions require that the desired temperature in the home be maintained with reasonable uniformity. A widely fluctuating temperature is conducive to colds and discomfort, and at the same time will require approximately as much fuel as if the temperature had been maintained at the desired value. With the customary hand firing, the judgement and attention of the individual attending the furnace, often the woman of the house, is relied upon to shovel in the coal and to control the dampers and thereby control the temperature. Too often this attention is diverted and the fire is forgotten, or one fails to judge correctly when to open or close the draft, with the result that the house gets either too hot or too cold.

By means of automatic temperature controls, it is practicable to control the dampers of a furnace to automatically maintain any desired temperature in the living room with but a relatively small variation throughout the day. Such an automatic control may readily be applied either to a handfired furnace or to an automatically fired furnace and includes a thermostat located usually in the living room. This thermostat is electrically connected to control the dampers in the case of the handfired furnace, or the automatic stoker in

*For assistance in conducting tests and making observations on stoker installations the author is greatly indebted to H. V. Carpenter, Stanley A. Smith, Eri B. Parker, G. E. Thornton, Geo. Lommasson, and A. C. Abell. The author wishes particularly to mention the valuable assistance and many helpful suggestions given by Mr. Howard H. Langdon.

the other case, and is set to maintain some certain desired temperature in the room in which it is located. If for any reason it is desired to maintain a higher or lower temperature, this can be accomplished by moving a pointer on the thermostat and the new order will be carried out automatically.

With the handfired furnace it is necessary to replenish the fuel supply by hand from time to time. This requires some attention throughout the day With the automatically fired furnace it is customary to introduce a relatively large charge of fuel into the automatic device at one time, and this is drawn upon from time to time to supply the fuel for the fire. A suitable size charge of fuel may be introduced in the morning or during the evening, according to the habits of the person attending the furnace, and will last without further attention for a period as long as twenty-four hours or more.

FUEL FOR DOMESTIC HEATING

Fuel for household heating may consist of wood, coal, oil, or gas In any case the fuel consists of a certain percentage of carbon which during the process of combustion unites with the oxygen of the air to form heat It is important that complete combustion take place, otherwise part of the heat value of the fuel in the form of unburned carbon will escape up the chimney as smoke,—fuel deliberately thrown away into the air—later to smudge the family laundry.

FUEL COMBUSTION

In the ordinary operation of a furnace, the fuel is introduced by throwing it on top of a bed of coals. The new fuel cools the top of the fire, until the temperature of the new fuel is raised to the point of combustion During the interval, there results a more or less dense cloud of smoke which represents valuable fuel gas distilled from the new fuel, but the fire being cooled off does not supply sufficient heat to ignite and burn the escaping gases. As a result they are lost up the chimney. Furthermore, they cover the walls of the furnace with a layer of soot—an effective heat insulator—preventing the transfer, into the rooms of the house, of the heat derived from that part of the

fuel which is burned. This is illustrated in Figure 1 It is estimated that one-fifth of an inch of soot equals one inch of asbestos in heat insulating ability, and it is conceded that no one would think of lining his furnace with asbestos.

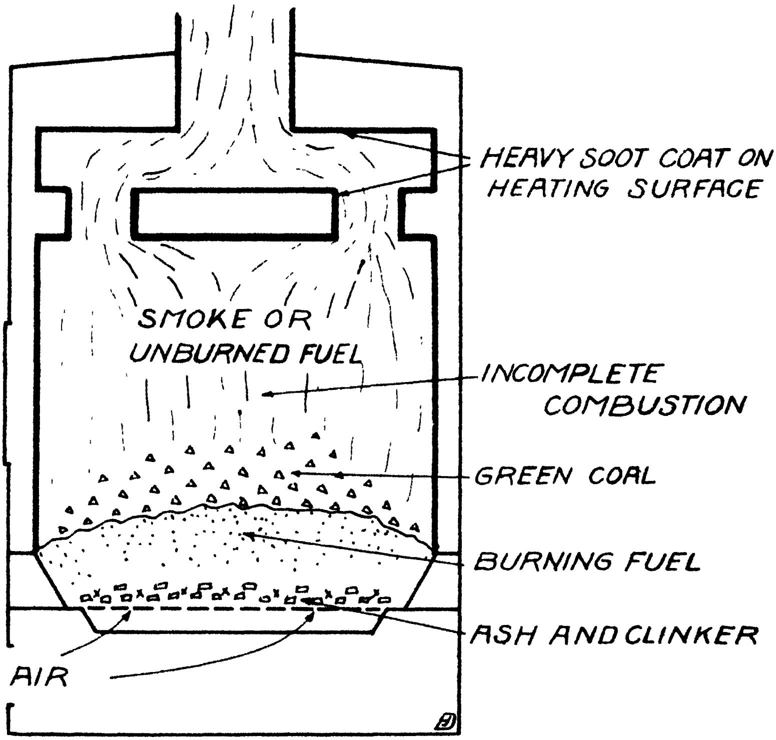

Figure 1 A hand fired furnace showing poor combustion taking place when fresh coal is placed on top of the fire.

In order to accomplish complete combustion, it is necessary to proportion properly the amount of air and fuel being burned. An excess of air is not only useless but it also absorbs heat to raise its temperature and carries the heat up the stack with it. Lack of air prevents complete combustion and therefore causes loss of fuel in unburned gases.

Fuel contains, among other things, a certain percentage of "fixed" or pure carbon. When heated to a sufficiently high temperature, and

in the presence of sufficient air, this carbon unites chemically with the oxygen of the air resulting in what is known as combustion of the fuel. When one pound of pure carbon burns completely to carbon dioxide, CO_2, there is generated or liberated 14,544 B.T.U.'s* of heat. If insufficient oxygen is supplied, partial combustion takes place, resulting in the formation of CO, and only 4,351 B.T.U.'s of heat are liberated—less than one third of the total heat value of the fuel. The remainder goes up the chimney in the form of unburned CO gas.

Such large heat losses attend the customary top feeding of domestic furnaces and cannot well be avoided. Logically, one would be loath to throw out of doors one shovel full of fresh coal for every four or five he placed in the furnace, but that is virtually what takes place when he puts green coal on top of his furnace fire. Part of this fuel loss can be avoided by exercising proper care in firing--which the average person does not do.

Coal may also be burned by introducing the fresh cold fuel into the bottom of the fire, the gradual heating thereof by the fire above slowly distills off the volatile matter which proceeds up through the hot fuel bed and is ignited and burned more or less completely, depending upon the amount of air being supplied. Later the coked fuel ignites and becomes a part of the hot fuel bed—new green coal being introduced from below to enable combustion to continue. This method results in much more complete burning of the gas which is always given off by the green coal and so causes minimum sooting of the furnace walls.

From the above, it will be seen that top feeding of a furnace fire results in a loss of fuel and fouling of the furnace walls with soot, the latter making for reduced efficiency of heat transfer.

Underfeeding of a furnace fire makes possible the complete combustion of the fuel with maximum possible realization of the total heat value of the coal.

* One British Thermal Unit represents the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.

THE AUTOMATIC UNDERFEED STOKER

During recent years methods have been perfected for introducing fuel, particularly coal, into a domestic furnace from the bottom of the fire, and for making the operation more or less continuous and automatic. By means of a small electric motor, coal is forced up under the fuel bed and at the same time air under pressure is supplied to promote combustion. By properly adjusting the relationship between the rate of coal fed and the amount of air introduced combustion can be maintained at its fullest efficiency.

While manufacturers have attempted to develop a successful stoker based upon the top firing principle, the greatest progress has been made in developing the underfeed type In the underfeed stoker, fuel is introduced into the fuel bed either by menas of an oscillating ram, or plunger, or by the use of an auger or screw conveyor. The method of introducing fuel into the underfeed furnace , if mechanically reliable, would appear immaterial—the important feature being the rate of feed as compared to the rate of combustion Some attempt has been made to automatically remove the ashes or clinkers from the underfeed stoker furnace but this has not met with unqualified success, because the removal of clinkers is often accompanied by the removal of excess fuel which has dropped into the clinker or ash compartment

The type of stoker which has been developed most successfully employs a screw conveyor for introducing fuel into the bottom of the fuel bed and requires the removal of accumulated clinkers from the fire through, what would otherwise be, the usual firing door of the furnace. These clinkers accumulate around the edge of the fire as in Figure 2 and must be removed by means of clinker tongs.

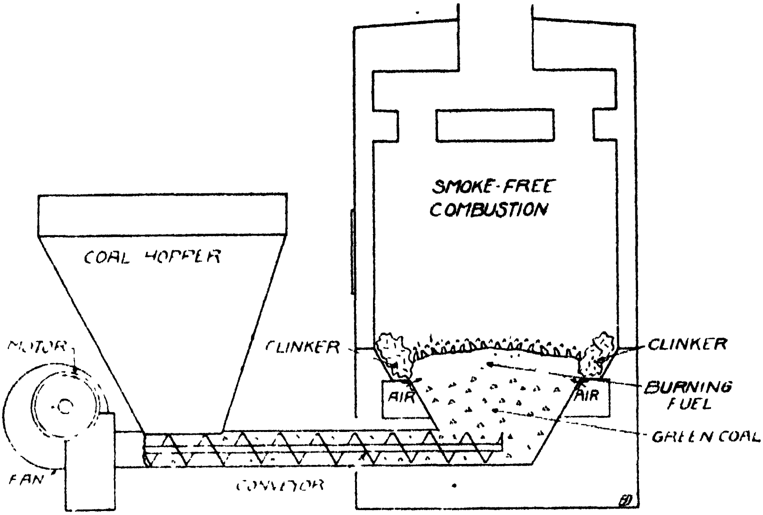

Figure 2. A stoker equipped furnace showing the method of introducing fresh coal into the bottom of the fuel bed

EFFICIENCY OF FUEL COMBUSTION

Theoretically, the ideal method of firing a furnace would be to introduce and burn the fuel continuously and only fast enough to supply the necessary heat In this method the relationship between fuel and air would be established and combustion would be maintained at the highest possible efficiency.

Practically, it has been found that the average domestic heating load varies and fluctuates throughout the day and from day to day, so that it has been considered more satisfactory to operate the furnace at comparatively high efficiency for a short period at a time, permitting the intervening intervals to constitute a more or less idle period for the fire. While combustion continues during the idle period and at very low efficiency, nevertheless, the amount of fuel burned during such period is comparatively small and the percentage thus wasted of the total fuel burned is relatively small

THE OPERATING CYCLE OF THE STOKER

Because of the greater ease of control, the stokers on the market at the present time are built to work on the principle of intermittent operation, the length of the period of operation and the frequency

thereof depending upon the demand for heat. Thus, when the room temperature reaches a predetermined minimum, the room thermostat will start the stoker, which will continue to operate until the room temperature reaches a predetermined maximum.

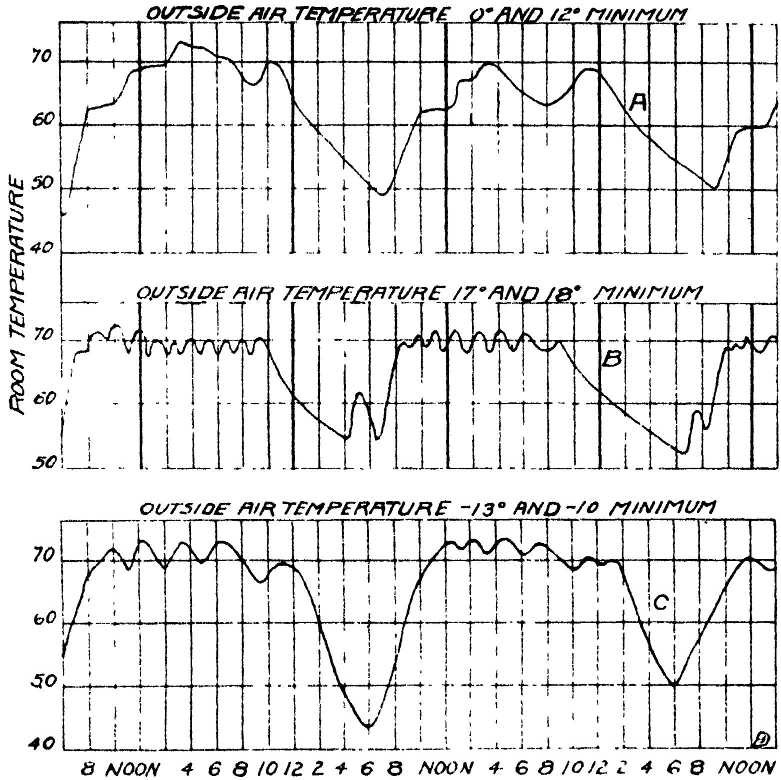

Figure 3. Temperature records for forty-eight hours taken in the living rooms of three different furnace heated homes.

Curves A and B in Figure 3 show living room temperatures of houses heated with warm air furnaces. The furnace in the case of Curve A is hand fired and the relatively large variation of temperature throughout the day will be noted. In the case of Curve B which is taken from the living room of a stoker fired hot air heated house, it will be noted that the desired average temperature is maintained with

but small variation throughout the day. Owing to the small amount of stored heat in a hot air furnace system, it will be seen that the stoker must operate every hour or hour and a half.

Curve C, representing a hot water heated house, was taken during sub-zero weather, and in spite of the low outside temperature, it will be noted that the stoker operated less frequently than in the case of the warm air furnace.

The temperature range in B is approximately 3 degrees, while in the case of C it is between 4 and 5 degrees. This is due to the adjustment of the room thermostat and has nothing to do with the type of furnace used.

RELATIVE MERITS OF HOT AIR AND OF HOT WATER FURNACES

It is not the object of this study to go into the matter of the relative efficiency of the hot air and the hot water furnaces, but rather to discuss the matter of efficiency of burning coal by means of the underfeed stoker.

TESTS OF STOKER INSTALLATIONS

During the winter of 1928-1929 a series of tests were made on several different automatic coal stokers installed in different Pullman homes for domestic heating. By means of recording instruments the amount of coal used per day was measured. To accomplish this the instrument registered the number of revolutions of the coal auger. By weighing the amount of coal used over a period of several days and noting the number of revolutions of the auger the pounds of coal delivered per revolution could be determined. Such data shown in Table 1 was obtained for the six residences on which tests were made, and shows the recorded coal consumption per month for each furnace. The type furnace in indicated as is also the amount of radiation, and the cubical contents of the house. Figure 4 shows a typical daily coal consumption curve for a stoker-equipped hot water furnace. It will be noted that as the outside air temperature goes down the coal consumption goes up.

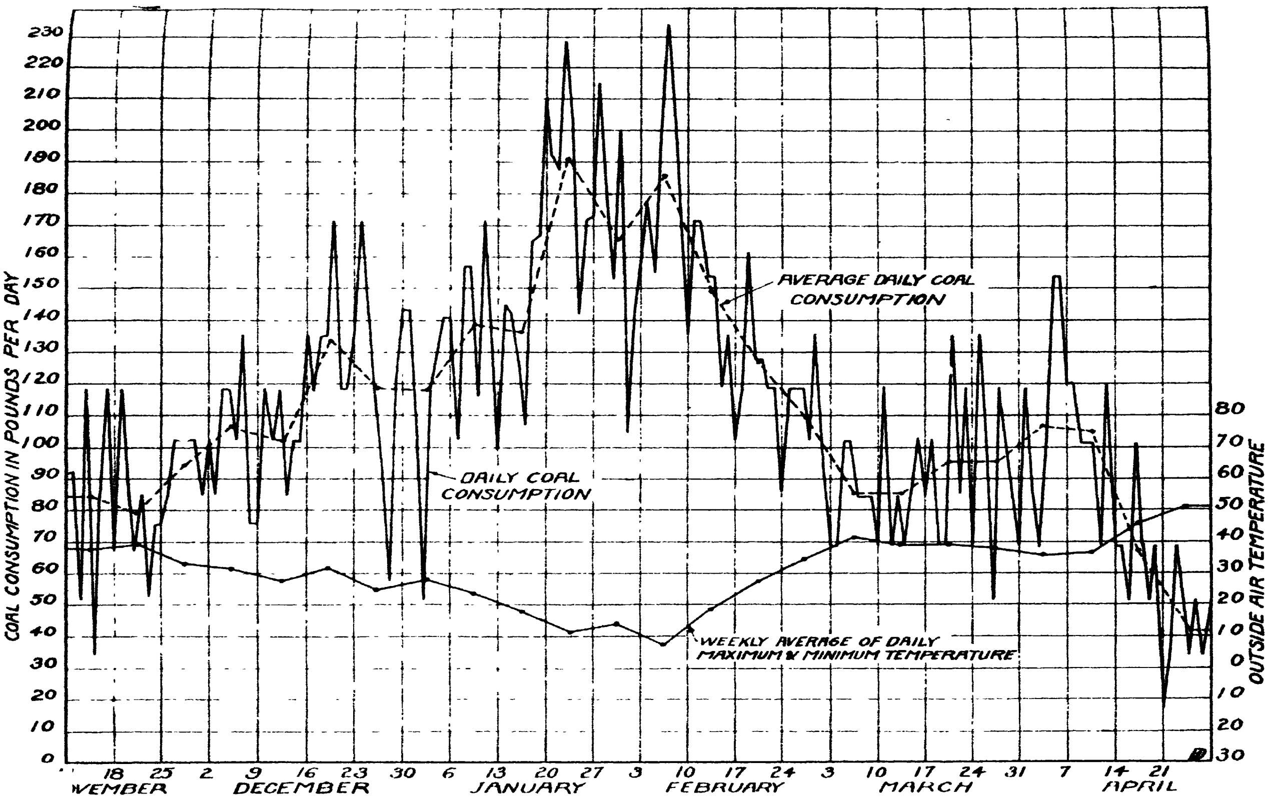

Figure 4. Daily coal consumption record of the author's stoker fired furnace

TABLE I

No.	Heating System	Type of Firing	Cubical Contents of Building	Sq Ft Radiation	Coal Burned—Pounds Per Month					
					Nov.	Dec.	Jan	Feb	Mar.	Apr.
1	Hot Air	Stoker	13,250	......	... ...	3287	3693	2905	2148	2045
2	Hot Air	Stoker	22,320	......	.. . ..	....	4854	3000	2002	1657
3	Hot Water	Stoker	17,250	326	2469	3488	4731	4057	2753	2360
4	Hot Water	Stoker	15,200	385	....	3685	4412	3900	....	....
5	Hot Water	Stoker	26,470	519	....	....	4640	4610	3224	....
6	Hot Water	Hand Fired	19,444	399	....	....	4370	4038	....	....

KIND OF FUEL BURNED

Several different kinds of coal were burned in the tests. In all cases, the grade of coal was what is known as slack. A stoker requires a fairly fine fuel, which also happens to be cheaper than the usual lump coal burned in a furnace. In fact, the rapid development of the domestic stoker has been partly due to the fact that it can successfully burn the cheaper grade of fuel. This fuel, known as slack, usually contains as much or more heat per pound than the higher grade coals, excluding of course, the dirt or other non-combustible material. The reason it cannot be successfully burned in the average furnace is due to the large amount of draft necessary to get the required amount of air up through the fuel bed. The stoker supplies this required draft

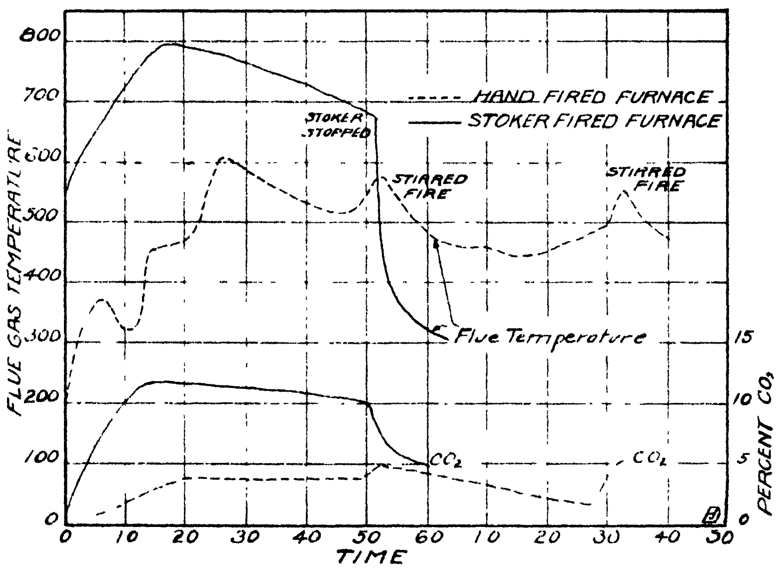

Figure 5. Comparative tests on hand fired and stoker fired furnaces

In figure 5 is shown the relative performance of a hand fired and of a stoker fired furnace in which tests were made of the products of combustion and of the flue gas temperatures. In any fire, the proper mixture of fuel and oxygen will give complete combustion as indicated

by a high percentage of CO_2 and an absence of CO Theoretically, the percentage of CO_2 cannot possibly exceed 20.9%, but in common practice 15% is considered about the highest attainable. In the case shown in Figure 5, the hand fired furnace shows an average CO_2 of 4% against 11% for the stoker fired furnace. Both cases represent average firing with no attempt towards special results for the tests. In the case of the hand fired furnace, approximately 30% of the present fuel loss is preventable if the fuel could be burned under the correct conditions, while with the stoker fired furnace, only a little over 4% preventable fuel loss is taking place.

In the average domestic furnace, the combustion space is frequently too small, resulting in the burning gas striking a comparatively cool surface before combustion is complete. This cools the gas and results in incomplete combustion with a consequent waste of fuel Some furnaces have very short gas passages from the fire box through the furnace to the chimney as if the object were to get the gas into the chimney with the minimum possible reduction in temperature. This helps to give a strong draft but all the heat which escapes up the chimney is lost as far as concerns heating the house. Practically, it has been found necessary in ordinary residences to permit considerable heat to escape up the chimney in order to provide the necessary draft for the fire. A stoker reduces this requirement so that the flue gas temperature might as well be reduced to 300° or 400° Fahrenheit. In Figure 5 it will be noted that the flue gas temperature ranges from 600° to 800° Fahrenheit maximum, which means that the gas passages in the furnace are too short, or the heating surfaces are badly soot-covered, allowing too much heat to escape up the chimney. In one residence furnace under test, the flue gas temperature under the worst condition was found to reach as high as 1300°, indicating that over one-half the heat was being thrown away.

COALS USED IN STOKER TESTS

Most of the coal burned in the five stokers noted was slack from Aberdeen, Utah. Small quantities each of Ravensdale, or McKay washed stoker coal, and of Wyoming Rocksprings Star were burned also in one of the stokers under test. The amount of ash per pound

of coal as found by weighing the clinker over a period of time was found to range from 3% to 5% by weight. No marked difference was noted in the behavior of these different coals in the furnace either as to burning or as to clinker forming characteristics. All three are of the free-burning type.

On the basis of the foregoing statements, it may be assumed that by installing an automatic underfeed coal stoker, the coal will be burned much more efficiently and therefore a smaller amount of coal will be consumed during the season. Theoretically, this is true Actually, however, the added ease and convenience of heating a residence with a stoker serves to induce the owner to maintain the temperature of his home more comfortably and for a greater part of the 24 hours, with the result that he will probably burn about the same number of tons of coal as by the usual hand firing methods. The grade of coal used in the stoker, however, costs 30% to 40% less than the lump coal for hand firing The total result is that the householder will enjoy more temperature comfort in his home, will maintain more healthful living conditions for himself and family, will relieve himself and his family of the need for constant supervision of the heating plant, and will do all this for a little less than his usual coal bill.

FURTHER TESTS

During the coming year these studies will be continued along at least two lines; namely, the behavior of different coals in the stoker fired furnace, and the comparative efficiency of combustion as controlled by furnace design. Judging from the high flue gas temperatures found to be prevalent in both hand fired and stoker fired furnaces, it is apparent that a considerable percentage of preventable heat loss is taking place up the chimney in the average furnace installation. Investigation will be made of the possibility of increasing the length of the gas passages in a stoker-fired furnace in order to reduce the flue gas temperature and thereby further increase the coal economy of such a furnace. There seems to be some promise of success in this since the stoker blast serves to replace a large part of the draft otherwise required for combustion in the ordinary furnace, and since the stoker fire does not deposit so much soot on the heating surfaces.

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2. How to Measure Water.
By O. L. Waller, October, 1915, Reprint 1925 (Revised and Reprinted as part of Engineering Bulletin No. 20.)

3 Water Supply for the Country Home. (Out of Print.)
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// MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Volume 11 | April, 1930 Second Edition | No. 11

FIRST PROGRESS REPORT

A Study of Welded Metals Under Fatigue Tests

by

G. E. Thornton

Department of Mechanical Engineering

ENGINEERING BULLETIN NO. 34

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

September, 1930

Entered as second-class matter September 5 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

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A STUDY OF WELDED METALS UNDER FATIGUE TESTS

By

G. E. Thornton*

OBJECT

The object of the tests undertaken in this work was to compare the different type of welds in which a flexure of the specimen occurs when subjected to a continuous series of stress reversals. Such a condition is present in a member under continuous or spasmodic vibration.

The tests were undertaken by the Engineering Experiment Station of The State College of Washington in cooperation with the Mechanical Engineering Department of the same institution and with the American Welding Society.

The field covered in this work consists of tests of oxy-acetylene welds, resistance welds, and flash welds, and some work on atomic hydrogen and metallic arc welds.

In determining a policy of securing specimens it was decided to test small specimens in fatigue instead of the large specimens advocated by some companies

It was decided to obtain a true cross-section of the welding field by soliciting welded coupons from companies doing different types of welding. The average of these tests gives a lower result than would be obtained if one experienced man was doing all the welding with the knowledge that his welds were to be tested for test data.

The author feels that this cross-section of the entire field is much more of an indication of what to expect from welds than the best results obtained by any one individual.

*The author wishes to express appreciation for valuable assistance and co-operation given him in this work by Mr. Joseph F. Mills and Mr. Douglas Blake, Graduate Students in Mechanical Engineering, and Mr. George Lommasson, Instructor in Machine Shop Practice, also for test specimens furnished by the General Electric Company, the Union Carbide and Carbon Company, the Air Reduction Sales Company, and the American Chain Company.

APPARATUS

The apparatus used in connection with this work consisted of a bank of seven Farmer Type rotating beam testing machines. The construction of the machines was the construction usually employed for testing a short specimen.

The specimen, Figure 1, reduced at the center and tapered at the ends, was pressed into the end of the spindle of the test machine which was machined to fit the end of the specimen. The specimen was securely held to the spindle at each end by means of a ¼" machine screw.

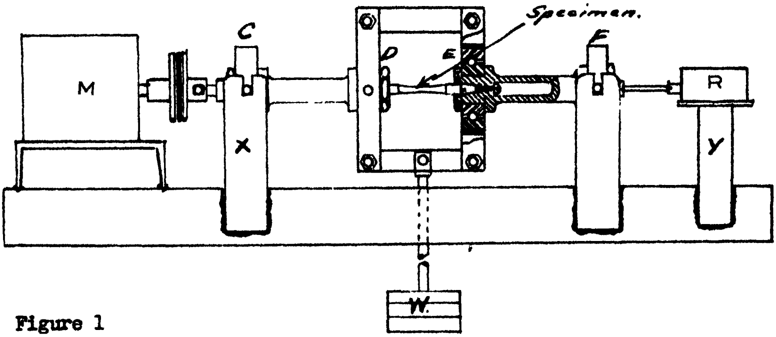


Figure 1

Figure 1. Line drawing showing construction of Farmer Type rotating beam testing machines used in fatigue tests.

The two spindles with the specimen securely fastened between them was free to rotate in the set of four roller bearings, CDEF Two of these bearings, C F, were mounted on trunnions resting in the slots in the end brackets X Y. The other two bearings with connecting cross bars formed a yoke which supported the weight W.

By varying the weight W any desired stress could be placed on the specimen to be tested.

The specimens were rotated by a one-fourth h.p. motor M direct connected by a universal coupling to the spindles holding the specimens.

The machine was shut down as soon as the specimen failed by means of an automatic drop switch on the rod holding the weight.

The number of reversals which each specimen completed was recorded upon a revolution counter R connected to the end of the spindle opposite the driving motor.

Figure 2. Close-up view of Farmer Type rotating beam fatigue testing machine.

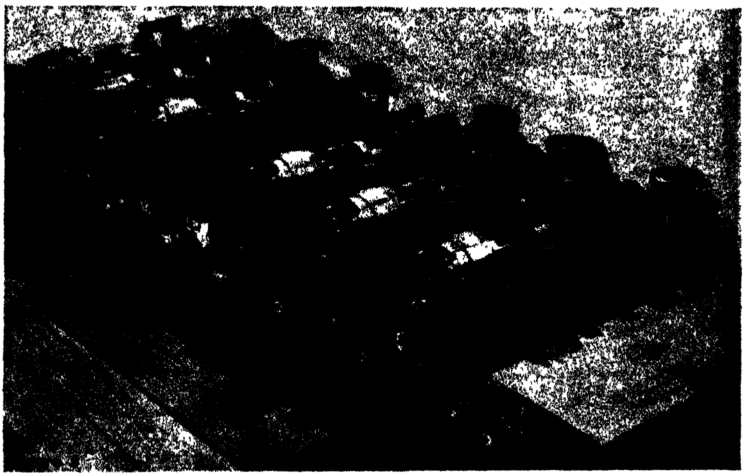


Figure 3. Bank of fatigue machines used in obtaining data on fatigue of welds. Same construction as shown in Figure 2.

SPECIMENS

The specimens for test were furnished by the General Electric Company, Union Carbide and Carbon Company, Air Reduction Sales Corporation, American Chain Company, and the welding shops of the Department of Mechanical Engineering, State College of Washington.

The specimens were made up by cutting cross sections from a test coupon formed by welding two ¾" x 2½" bars of fire box steel 24" long, as shown in Figure 4.

The sections cut from the coupon were ¾" square and 5" long. These small sections were then turned down to ½" diameter and the center section reduced to .400" diameter (Figure 5). The center

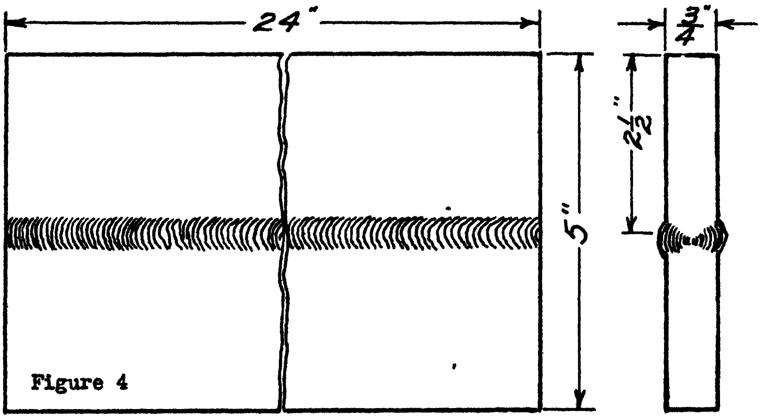


Figure 4. Method of making up coupons from which specimens were cut.

section was reduced for the purpose of causing the specimen to fail in the weld. This procedure was successful in concentrating the flexure of the specimen at the weld and thus gave a means of comparison between the different types of welds.

The specimens were highly polished at the reduced section in order to eliminate the possibility of small depressions inducing premature failure when subjected to a bending stress.

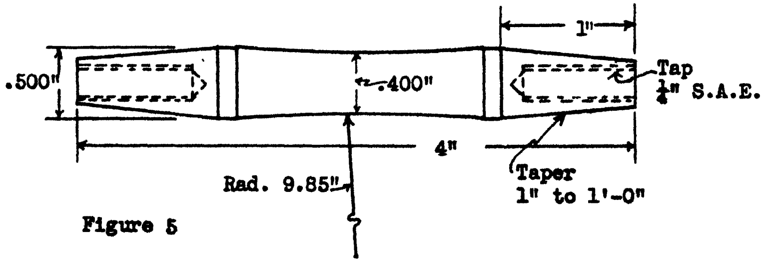


Figure 5. Line drawing of fatigue specimen used in tests.

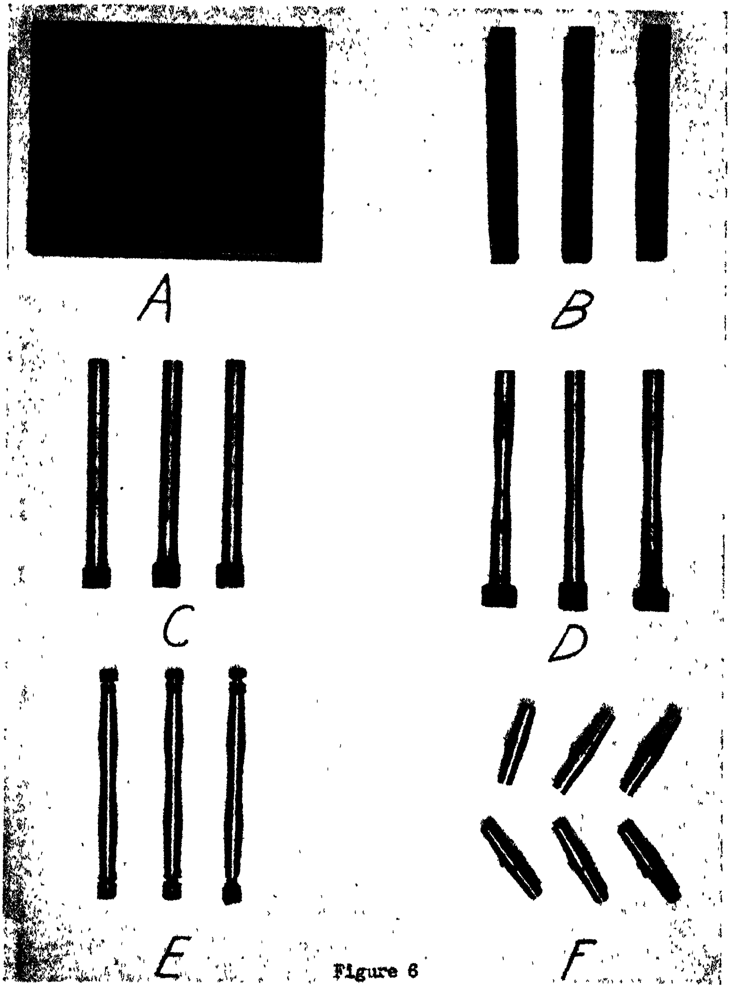


Figure 6. Progressive stages in preparation of specimens from welded coupons used in fatigue tests.

A. Coupon as received from manufacturing company.
B. ¾" square bars sawed from coupons.
C. ¾" square bars turned to ½".
D. Center section of ¾" specimen reduced.
E. Specimen polished, tapered at ends and tapped for ¼" cap screw.
F Specimen after being broken in test machines.

The specimens were carefully placed in the testing machine and fastened to the spindle to give a true, even rotation without vibration. The speed of rotation, 1750 R.P.M., was such that no whip was produced in the short specimen.

The same procedure was carried through for each of the tests on the various types of welds.

DATA

The determination of the stress and loads for the specimens used in the fatigue tests for rotating beam machines was calculated as for a simple beam supported at each end with two concentrated loads equidistant from the center.

The beam formula used in determining the stress at the center of the specimen is

$$S = \frac{W(L_1 - L_2)}{2\, I/c}$$

where (refer to Fig. 7)

S = Unit stress in extreme fibre of the specimen in pounds per sq. in.

I/c = section modulus in inches and for a circular member is $.0982d^3$ where d is diameter in inches of the specimen at center or critical section.

For a specimen .400″ in diameter at critical section:

$$S = \frac{W\ (L_1 - L_2)}{.01256}$$

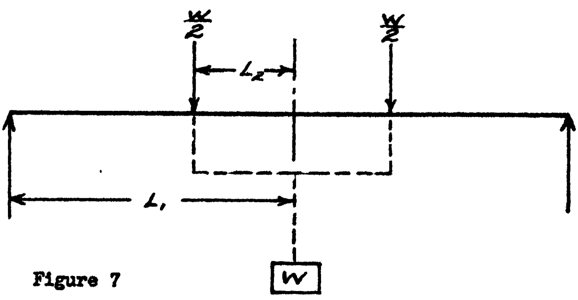


Figure 7

Figure 7. Position of loads and diagramatic sketch for determining stresses.

The weight of the bushings, bearings, and yokes which was included in the weight W, necessary to produce the stress, was

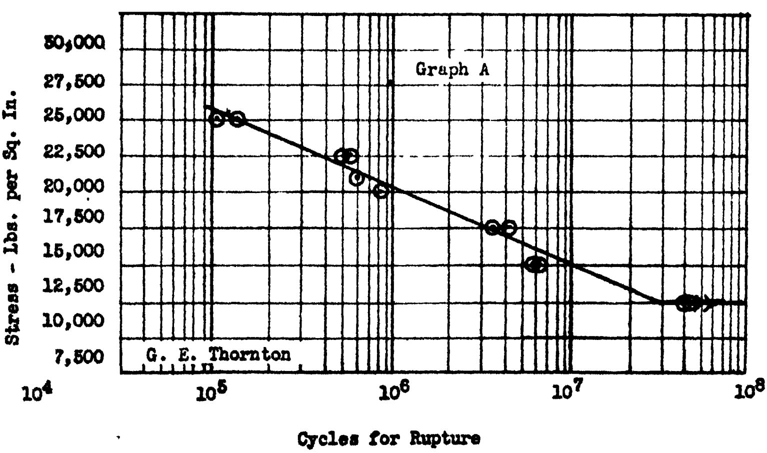
considered as being located one-half at either end of the yoke. The weight of the specimen itself, being small, was neglected.

The trunnions supporting the ball bearings were set on a flat face to give as near line contact as possible, thus reducing friction to a negligible amount. By the use of ball bearings the torsional stress applied to the specimen also became very small and was neglected in stress calculations.

Oxy-Acetylene Weld, Single V, Low Carbon Rod.
Ratio of Oxygen to Acetylene 1.14
A1 - Series
(See Graph A)

Stress	Specimen	Cycles for failure
25,000	L	138,700
25,000	J	102,500
22,500	G	565,000
22,500	I	546,000
22,500	H	31,000
21,500	O	600,000
20,000	K	822,000
17,500	D	3,600,000
17,500	F	4,080,000
15,000	C	6,380,000
15,500	B	6,120,000
*12,500	E	40,000,000
*12,500	M	40,000,000

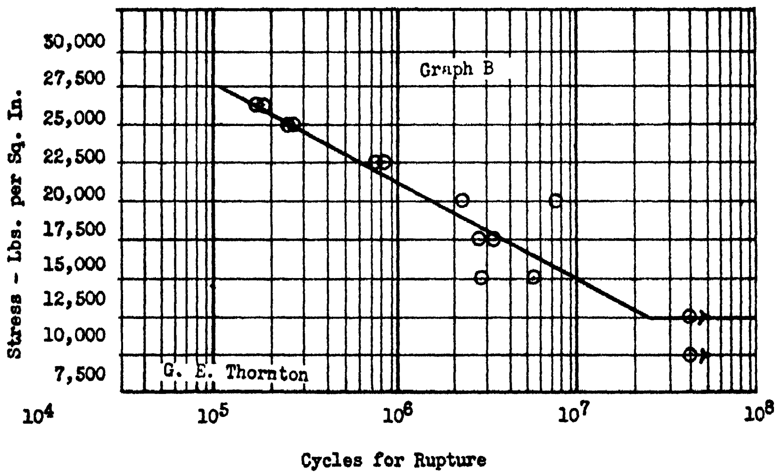
* Specimen did not break.



Oxy-Acetylene Weld, Double V, CR VA Rod
Ratio of Oxygen to Acetylene 1.08
A6 Series
(See Graph B)

Stress	Specimen	Cycles for failure
26,500	C	165,000
26,500	H	152,000
25,000	I	243,000
25,000	J	248,000
22,500	N	810,000
22,500	G	790,000
20,000	M	2,200,000
20,000	F	7,080,000
17,500	O	2,850,000
17,500	D	3,120,000
15,000	E	2,930,000
15,000	L	5,280,000
*12,500	B	40,000,000
*10,000	N	40,000,000

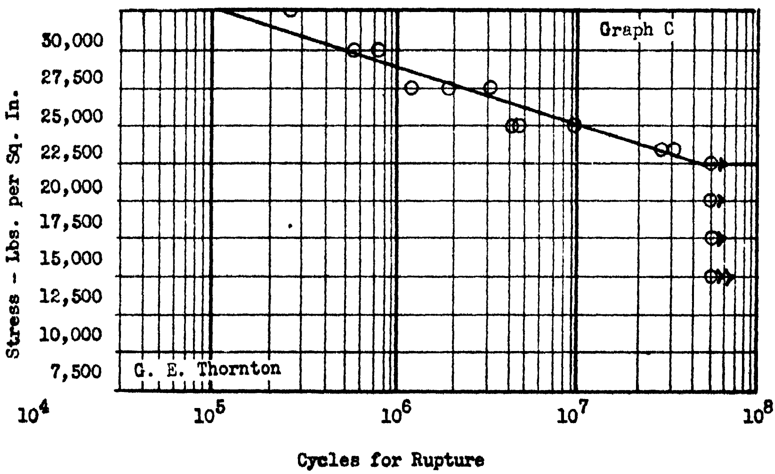
* Specimen did not break.



Resistance Weld
AC Series
(See Graph C)

Stress	Specimen	Cycles for failure
35,000	C	259,000
32,500	B	560,000
32,500	F	728,000
30,000	H	3,100,000
30,000	N	1,330,000
30,000	M	1,900,000
27,500	G	4,850,000
27,500	D	9,900,000
27,500	L	4,250,000
26,000	O	16,100,000
26,000	P	20,800,000
*25,000	J	40,000,000
*22,500	I	40,000,000
*20,000	E	40,000,000
*15,000	Q	40,000,000
*15,000	K	40,000,000

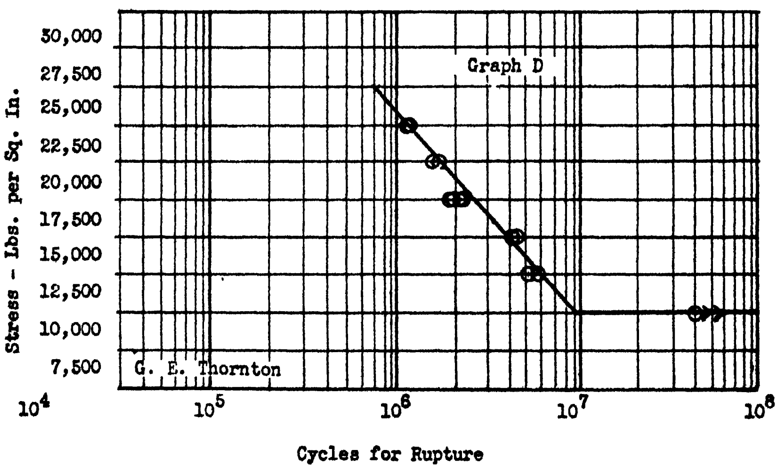
* Specimen did not break



Atomic Hydrogen Weld, Double V, 20 Amp. 50 V.
Filler Rod ⅛" Cr. Va. Oxweld
No. 3 Series
(See Graph D)

Stress	Cycles for failure
25,000	1,090,000
25,000	1,076,000
22,500	1,540,000
22,500	1,590,000
20,000	1,760,000
20,000	2,150,000
20,000	1,850,000
20,000	2,070,000
17,500	4,460,000
17,500	4,200,000
15,000	5,960,000
15,000	5,340,000
*12,500	40,000,000
*12,500	40,000,000

* Specimen did not break.
NOTE—Five specimens were eliminated from this group because of bad pits



Flash Weld

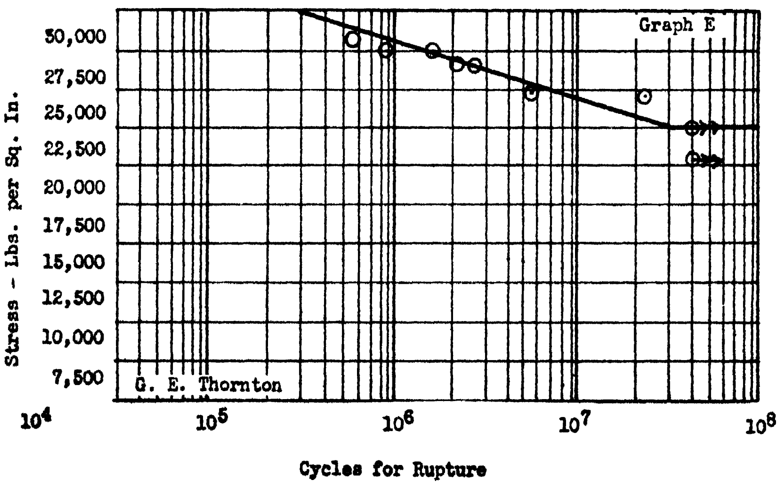
AC Series

(See Graph E)

Stress	Cycles for failure
31,000	598,420
30,000	889,000
30,000	1,520,000
29,000	2,040,000
29,000	2,519,000
27,000	5,620,000
27,000	12,820,000
*25,000	40,000,000
*25,000	40,000,000
*23,000	40,000,000
*23,000	40,000,000

* Specimen did not break.

NOTE—Two specimens in the group were bent in machining. Entire group were free from pits and hard spots.



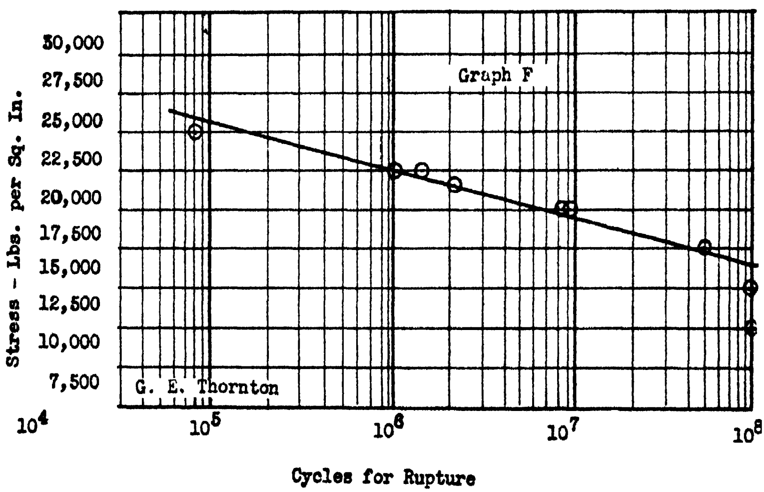
Metal Arc Weld, Single V
200 amp. using ⅛" low carbon rod
W1 Series

(See Graph F)

Stress	Specimen	Cycles for failure
25,000	A	80,200
22,500	I	1,400,000
22,500	C	1,000,000
21,500	D	2,050,000
20,000	H	9,200,000
20,000	B	8,400,000
17,500	E	40,001,700
*15,000	G	100,000,000
*12,500	F	100,000,000

* Specimen did not break.

NOTE—Welds were made by an old experienced welder with the knowledge that his work was to be tested. Method of Procedure was left to welder.



Metal Arc Weld, Double V, Lukens Steel Plate

210 Amp 3/16" Rod (F)

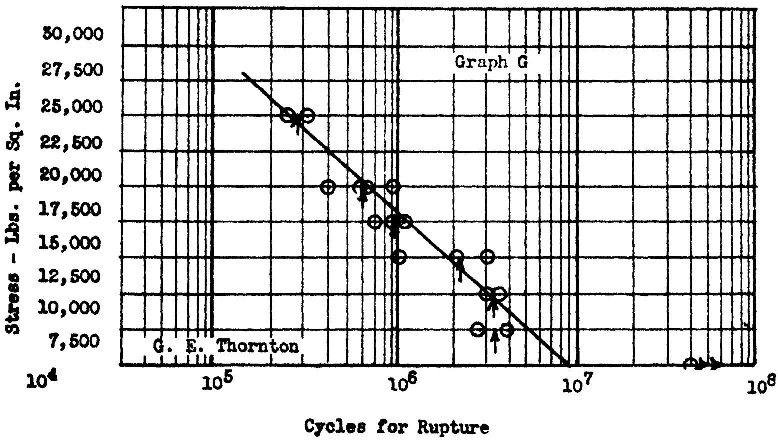
(See Graph G)

Stress	Specimen	Cycles for Failure	Ave.
25,000	1-2	262,140	
25,000	1-25	324,000	293,070
20,000	1-6	407,240	
20,000	1-22	963,000	
20,000	1-26	655,750	
20,000	1-8	619,150	663,785
17,500	1-16	725,900	
17,500	1-7	1,194,000	
17,500	1-10	986,000	968,630
15,000	1-11	1,179,000	
15,000	1-9	2,094,000	
15,000	1-3	3,208,000	2,160,513
12,500	1-1	3,495,760	
12,500	1-27	3,185,200	3,340,000
†10,000	1-29	814,000	
10,000	1-20	3,958,000	
10,000	1-23	2,890,050	3,424,025
* 7,500	1-18	40,000,000	
* 7,500	1-17	40,000,000	40,000,000

* Specimen did not break

† Badly pitted, probably an end section Not included in average.

NOTE—Average tensile strength 60,524 lbs per sq in.

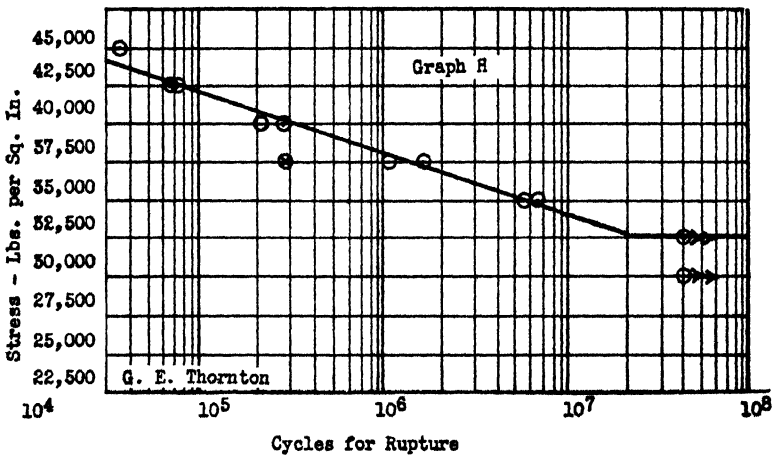


Parent Metal Fire Box Steel
15-20 A.S.M.E. Specification

(See Graph H)

Stress	Cycles for failure
45,000	34,700
42,500	64,000
42,500	71,000
40,000	282,000
40,000	204,000
37,500	1,742,000
†37,500	292,000
37,500	1,107,000
35,000	5,742,000
35,000	6,720,000
*32,500	40,000,000
*32,500	40,000,000
*30,000	40,000,000
*30,000	40,000,000

* Specimen did not break.
† Specimen bent.



Metallic Arc Double V

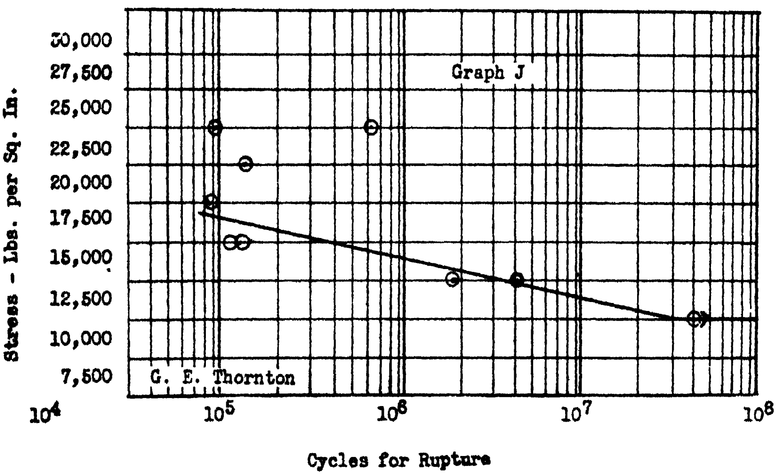
195 Amps 20 volts 3/16" rod

P 1 Series

(See Graph J)

P—1—K	27,500	18,800
P—1—F	25,000	95,000
P—1—I	25,000	708,000
P—1—E	22,500	142,500
P—1—N	20,000	88,400
P—1—J	20,000	†
P—1—M	17,500	110,000
P—1—G	17,500	140,000
P—1—D	15,000	4,050,000
P—1—B	15,000	1,910,000
†P—1—H	12,500	40,000,000

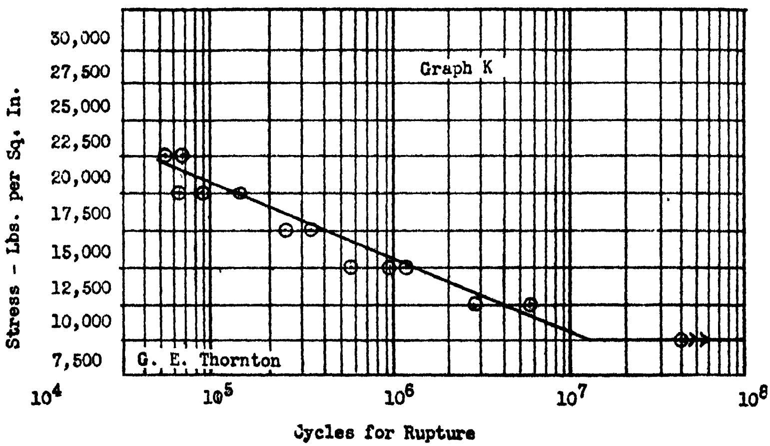
† Loosened in spindle.
* Specimen did not break.



Oxy-Acetylene Weld Double V Low Carbon Rod
Ratio Oxygen to Acetylene 1.04
A-4 Series
(See Graph K)

Specimen	Stress	Cycles for Failure
A—4—B	22,500	51,200
A—4—M	22,500	69,400
A—4—C	20,000	63,000
A—4—F	20,000	89,300
A—4—G	20,000	142,000
A—4—N	17,500	233,000
A—4—D	17,500	310,000
A—4—E	15,000	1,187,000
A—4—I	15,000	901,000
A—4—H	15,000	594,000
A—4—O	12,500	2,830,000
A—4—K	12,500	5,722,000
*A—4—J	10,000	40,000,000
*A—4—L	10,000	40,000,000

* Specimen did not break



Metallic Arc. Single V

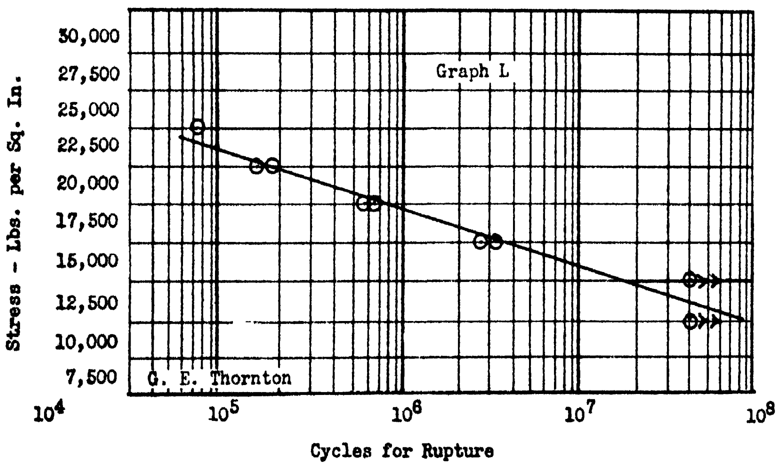
210 Amps. 5/32″ Rod Lincoln L. C.

W 3 Series

(See Graph L)

Specimen	Stress	Cycles for Failure
W—3—2	25,000	78,000
W—3—8	22,500	147,000
W—3—12	22,500	170,000
W—3—6	20,000	582,000
W—3—11	20,000	630,000
W—3—5	17,500	3,120,000
W—3—4	17,500	2,800,000
*W—3—3	15,000	40,000,000
*W—3—7	15,000	40,000,000
*W—3—10	12,500	40,000,000
*W—3—9	12,500	40,000,000

* Specimen did not break.



Oxy-Acetylene Weld

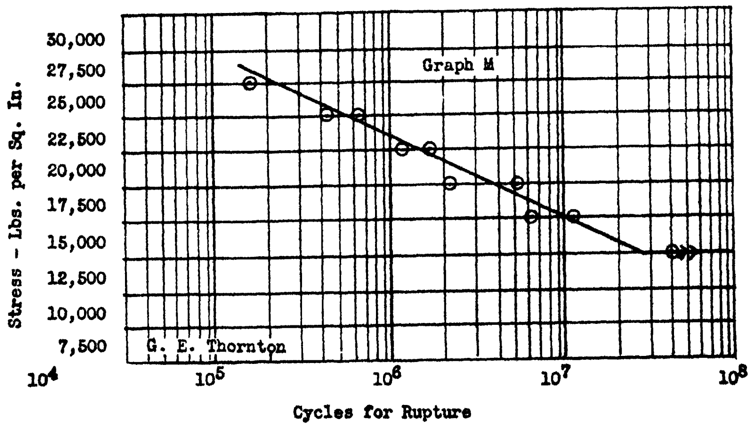
Single V Va. Welding Rod Ratio 1.00

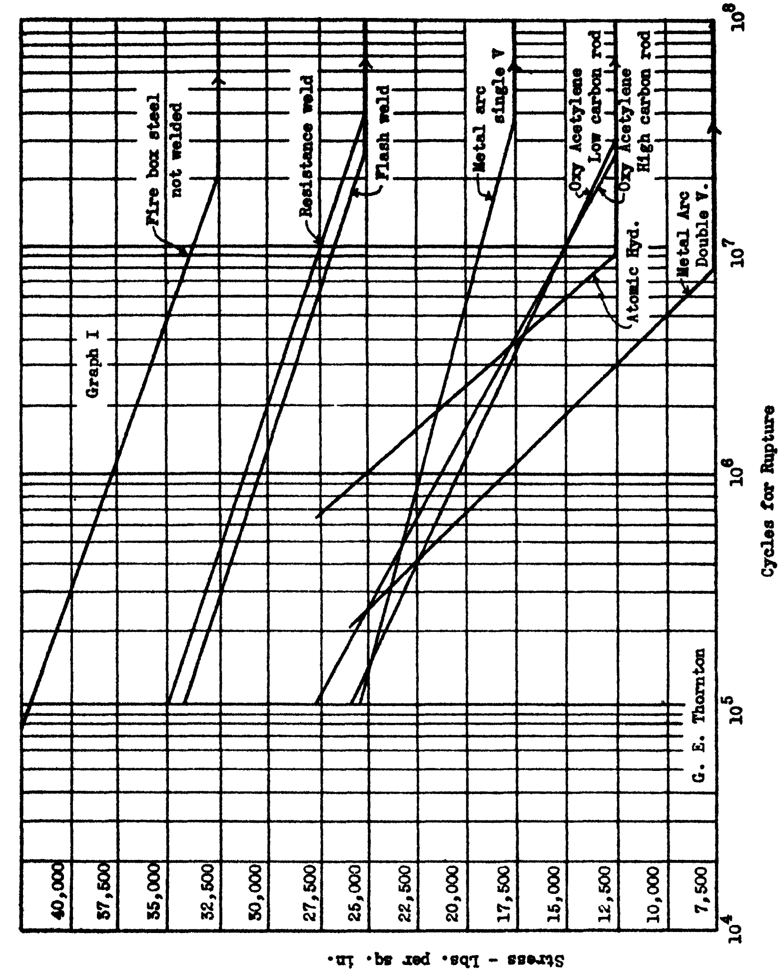
A 3 Series

(See Graph M)

Specimen	Stress	Cycles for Failure
A—3—B	27,500	171,000
A—3—G	25,000	432,000
A—3—F	25,000	661,000
A—3—M	22,500	1,721,000
A—3—N	22,500	1,322,000
A—3—L	20,000	2,090,000
A—3—I	20,000	5,120,000
A—3—K	20,000	†
A—3—J	17,500	6,421,000
A—3—C	17,500	10,038,000
*A—3—E	15,000	40,000,000
*A—3—D	15,000	40,000,000

* Specimen did not break.
† Specimen bent in machine.





Graph I
Fire box steel not welded
Resistance weld
Flash weld
Metal arc single V
Oxy Acetylene Low carbon rod
Oxy Acetylene High carbon rod
Atomic Hyd.
Metal Arc Double V.
G. E. Thornton
40,000
37,500
35,000
32,500
30,000
27,500
25,000
22,500
20,000
17,500
15,000
12,500
10,000
7,500
10^4
10^5
10^6
10^7
10^8
Stress - Lbs. per sq. in.
Cycles for Rupture

Atomic Hydrogen Double V
55 Amps 1/8 tungsten Electrodes
3/16" Armco Filler Rod
P 2 Series

Specimen	Stress	Cycles for Failure
P—2—E	27,500	15,335
P—2—I	27,500	11,275
P—2—L	25,000	9,225
P—2—C	25,000	15,375
P—2—M	22,500	29,725
P—2—N	22,500	5,125
P—2—D	20,000	132,125
P—2—F	17,500	12,360
P—2—K	17,500	870
*P—2—B	15,000	40,000,000
P—2—J	15,000	230,625

* Specimen did not break.
NOTE—Results were so erratic and scatter of points so great that no trend curve could be determined.

DISCUSSION OF GRAPHS

The lines in the graphs representing the results of fatigue at certain fixed stresses are by no means final and may be termed "trend lines" for the different types of welds. These lines furnish a basis for determining what to expect from vibration when no appreciable whip of the specimen occurs and when the deflection caused by such vibration of the specimen is not excessive.

The work in the metallic arc group was not as satisfactory on the whole as were the other groups. In the metallic arc welded specimens a larger number of pits and oxide spots were present than in the other types of welds. Some specimens in the metallic arc welded group ran high in endurance limit, while others ran very low. The specimens which showed pitting on the finished surface were excluded when making up the graphs.

An attempt was made to secure a metallic arc welded specimen from an experienced welder, who was aware that his welds were to be used in securing test data. The result of fatigue tests of this series of samples is shown in Graph F, Page 14. It is interesting to note that the welder, when left to his own method of procedure used 200 amp with a 1/8" low carbon rod, employing a short arc. This method, while producing a strong weld as far as fatigue is concerned

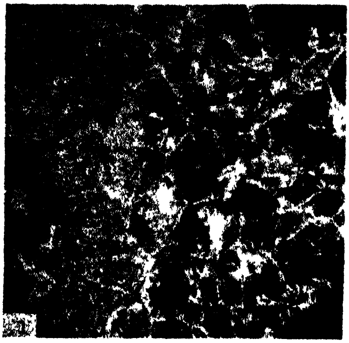
may not be an economical method of making a commercial weld because of the time involved. The penetration in this weld was excellent and the deposited metal very uniform.

The resistance and flash welds gave high values for resisting fatigue as shown by graphs C and E, pages 11 and 13 respectively. This is explained by the fact that the welds were free from pits, and oxide spots. This is due to the process of making the welds, since the arc produced in the welding operation excludes the formation of oxides and the formation of pockets from occluded gases. The welded metal is necessarily the same as the parent metal since no electrode or filler rod is used. A comparison between the welded metal and parent metal is well illustrated by comparing the micrographs, Fig. 18, Page 27. The light vertical streak through the central part of the upper micrographs shows the weld area. In this welded specimen this area is confined to a disc about 1/50 of an inch in thickness standing perpendicular to axis of specimen. There is a difference, however, in the hardness of the metal in the light streak representing the welded metal in comparison with that of the parent metal. This difference in hardness averaged about 20 points higher on the Rockwell B scale in the weld than in the parent metal for the 15-25 Fire Box Steel In the high carbon steels butt welded, there was noted a difference of 165 points on the Brinell scale between the welded area and the parent metal. The weld area was much the harder of the two.

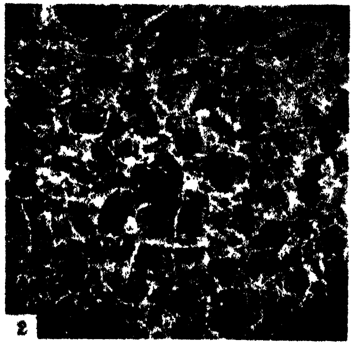
The trend line in Graph D, Page 12, for atomic Hydrogen is close to the average of 3 samples presented and is not complete. This type of weld seems to have a longer life for the higher stresses than do either the metalic arc or acetylene welds This, however, remains to be shown by a further series of tests.

Graph I, Page 21, shows the entire group of trend lines plotted to the same scale and gives a general idea of the amount of stress which each group has stood in comparison to that of the fire box steel (unwelded) which is shown as the top line of the graph.

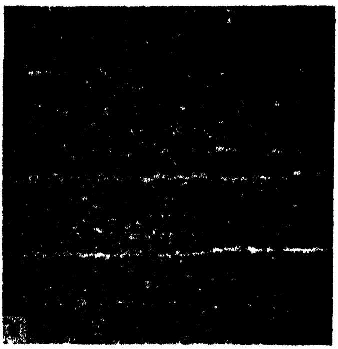
The flash weld and resistance welds have approached the nearest to the endurance limit of the fire box steel unwelded If the welds had been heat treated to give uniform hardness and grain structure, it seems possible that they would have equaled the original metal in endurance limit.



A—On weld line (95x)



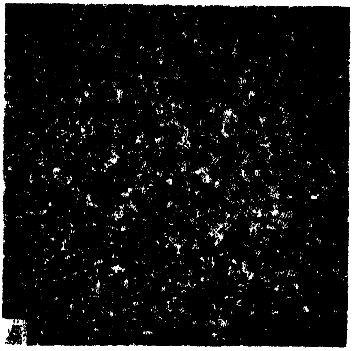
B—Parent Metal next to weld line. (95x)



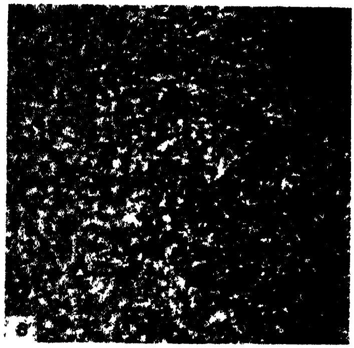
C—Parent Metal affected by heat from weld (.95x)

D—Parent Metal (95x)

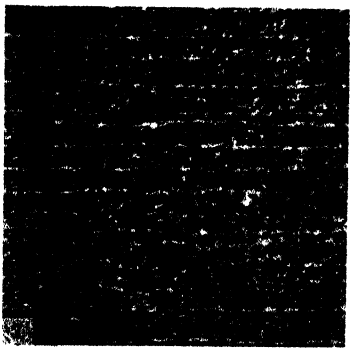
Figure 15. Metallic arc weld in Bethlehem Steel (C .16%, Mn .49%) using a 3/16" electrode with a current of 195 Amp.



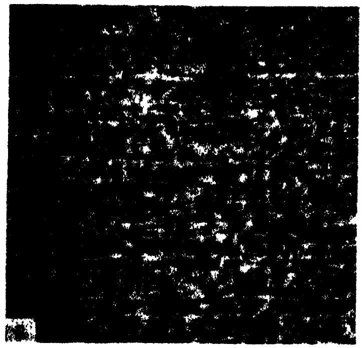
A—On weld line (95x)



B—Parent Metal next to weld line (95x)

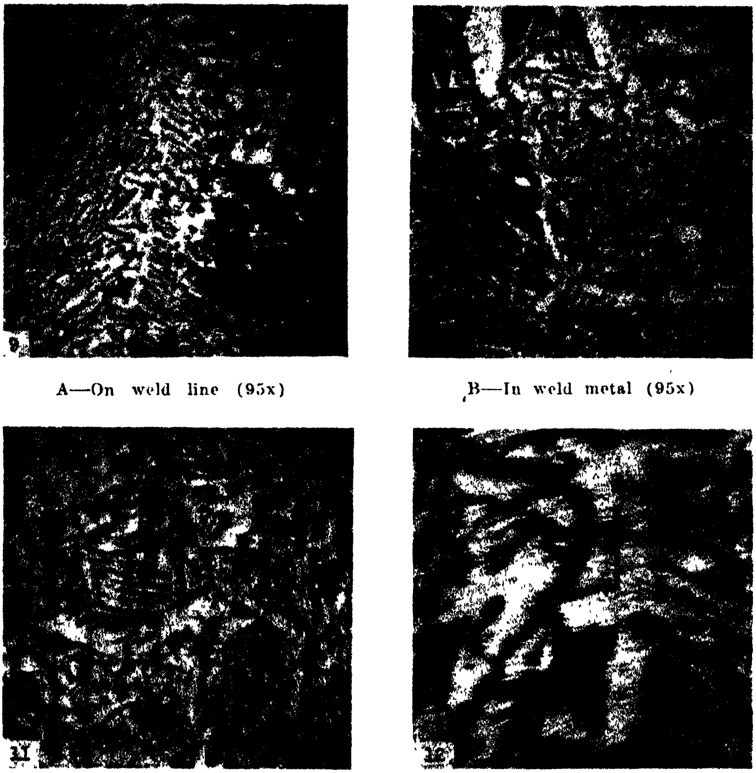


C—Parent Metal affected by heat from weld (95x)



D—Parent metal (95x)

Figure 16. Atomic Hydrogen Weld in Bethlehem Steel (C .16%, Mn 1.49%) using 3/16″ low carbon rod with ⅛″ tungsten electrodes with a current of 55 Amp



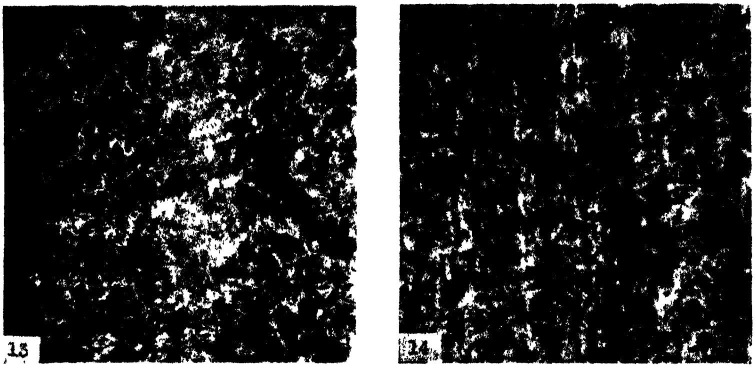
A—On weld line (95x)

B—In weld metal (95x)

C—Parent Metal (95x)

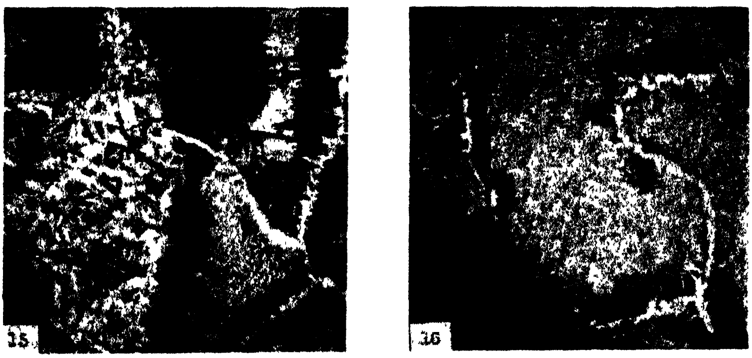
D—On weld line (350x)

Figure 17. Oxy-acetylene weld in boiler plate using vanadium welding rod with an oxygen to acetylene ratio of 1.



A—On weld line (95x) B—In Parent Metal (95x)

Figure 18 Flash weld using ¾″ cold rolled stock.



A— On weld line (95x) B—In weld metal (95x)

Figure 19 Oxy-acetylene weld in boiler plate using chrome-vanadium welding rod with an oxygen to acetylene ratio of 1.08.

DISCUSSION OF MICROGRAPHS

The micrographs of the different types of welds were made at 95 Diameters. All specimens were etched in a solution of 10% nitric acid to 90 % grain alcohol. The etching of the welded metal required a longer period than did the parent metal.

The micrographs show clearly that there are four areas in the welded region which are distinctly different considering them from the standpoint of grain sizes. Fig. 15, Page 24, shows these four areas:

A—The deposited metal at the weld line.

B—The Parent metal just outside the weld line.

C—The Parent metal to which has been given a very fine grain structure due to the heat from the weld.

D—The Parent or Stock metal itself.

The difference in grain structure in these four areas adjacent to each other has an important bearing on the endurance limit of the welded metals in fatigue.

All welded specimens present this difference in grain structure. The atomic hydrogen weld appears to give the smallest grain structure in the welded area and the oxy-acetylene welds showed the largest grain structure for the welds which were included in these tests.

In the oxy-acetylene welds employing a chrome-vanadium rod or a vanadium rod, a serrated grain boundary was noted in the welded metal. The grain boundary at A, Fig. 17, Page 26, is typical of this metal. An enlarged picture of this type of grain boundary is shown at D in the same figure.

From observations which were made, fatigue cracks at no time in any of the tests had their inception in these grain boundaries.

If the grain structure in the weld metal, the parent metal adjacent to the weld, and the adjacent parent metal itself could be made uniform in size, in all probability the endurance limit of the weld would be increased. This remains to be shown in further experiments with welded metals in fatigue.

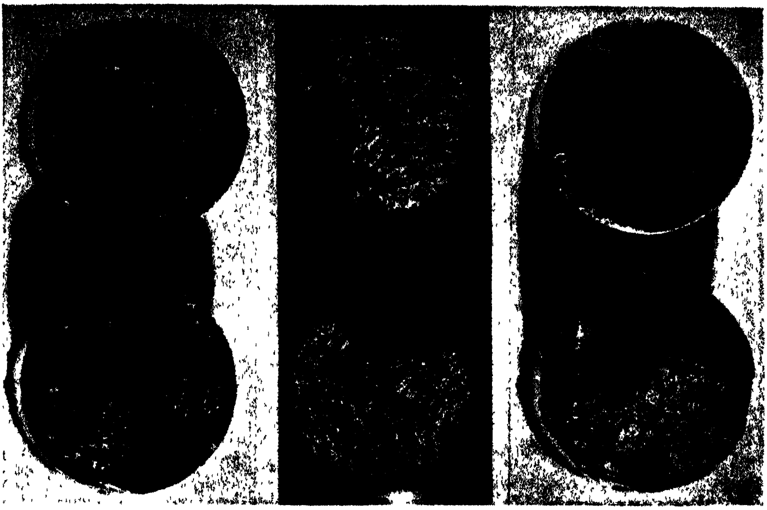


Figure 20. Typical fractures of welded specimens under fatigue test.
A. Metallic arc double V.
B. Oxy-acetylene double V.
C. Flash weld.
(4x)

Figures 20 and 21 respectively represent typical fractures of specimens when subjected to fatigue and tension tests.

From Fig. 20 it appears that the point of weakness was in the bottom of the V At the bottom of the V in many ruptured specimens the surface seemed worn smooth by a scrubbing action of two surfaces against each other, prior to ultimate failure.

The single V metallic arc weld and the single V oxy-acetylene weld appear much stronger in fatigue than does the double V weld. In the single V weld the bottom of the V has been removed in machining the specimen from the welded coupon. In a field weld of either the single V or double V type this condition at the bottom of the V is liable to exist.

It is yet to be determined if this failure at the center of the weld has been due to poor penetration or if the metal has in some way been weakened at this point in the welding operation.

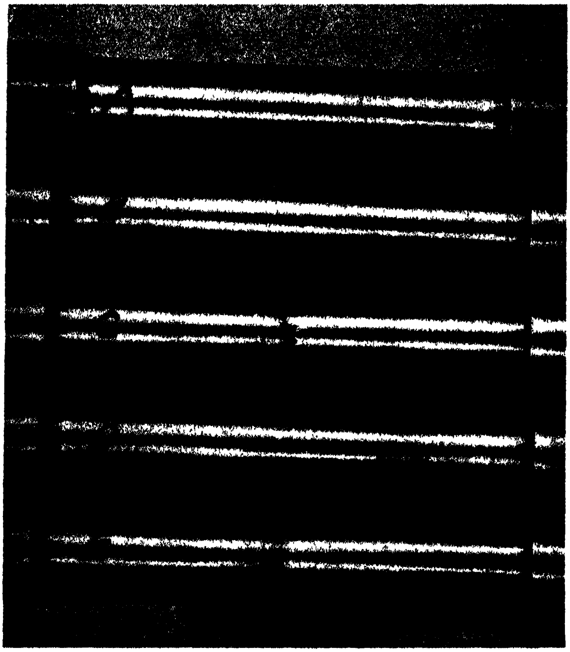


Figure 21. Typical fractures of welded specimens under tension tests.
A. Welded specimen, not tested.
B. Flash welded specimen.
C. Metal arc welded specimen, double V.
D. Resistance welded specimen.
E. Oxy-acetylene welded specimen.

The surfaces which are worn smooth by the scrubbing action appear to follow the plane of the scarf before the welding was begun.

CONCLUSIONS

It is at once apparent that welded specimens from fire box steel do not equal the endurance limit of that material unwelded. The three main reasons for such are:

1. Non-homogeneous structure due to oxide spots and pits caused from gas inclusions.
2. Difference in grain structure between the metal in the weld and the metal in the original bar.

3. Difference in hardness between the metal in the weld and the metal in the original bar.

The first mentioned reason is probably the most important in bringing on fatigue. The presence of the small holes in the metal is not so harmful as usually supposed unless present in such large numbers as to materially reduce the area of the cross section of the piece. The oxide spots and pits caused from gas inclusions during the welding operations can never be overcome by treating the weld and calls for further study along lines of shielding the arc by gases or other means in order to eliminate this objection and increase the endurance limit of welded steels.

The last two reasons mentioned for bringing on undue fatigue, namely grain structure, and hardness may be overcome by proper heat treatment. Such treatment is possible in a limited number of shop welded articles but from a commerical standpoint will probably never be economical with welds in the field.

The heat treatment of the weld will also help to eliminate the locked up stresses in the bar which have occurred in the welding operation. In certain cases these stresses have been determined as high as 25,000 to 35,000 lbs. per sq. in. When we consider these stresses in conjunction with the bending action of the metal in the rotating beam in which we have present the forces in tension, in compression, and in shear, it is at once evident that the determination of total stresses in untreated commercial welds can never be determined accurately.

This study will be continued with tests on the different types of shielded metallic arc welds and on specimens of all types of welds which have been uniformly heat treated.

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OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 12 July, 1929 No. 2

Short Wave Transmitter Design

by

David H. Sloan

ENGINEERING BULLETIN NO. 29

ENGINEERING EXPERIMENT STATION

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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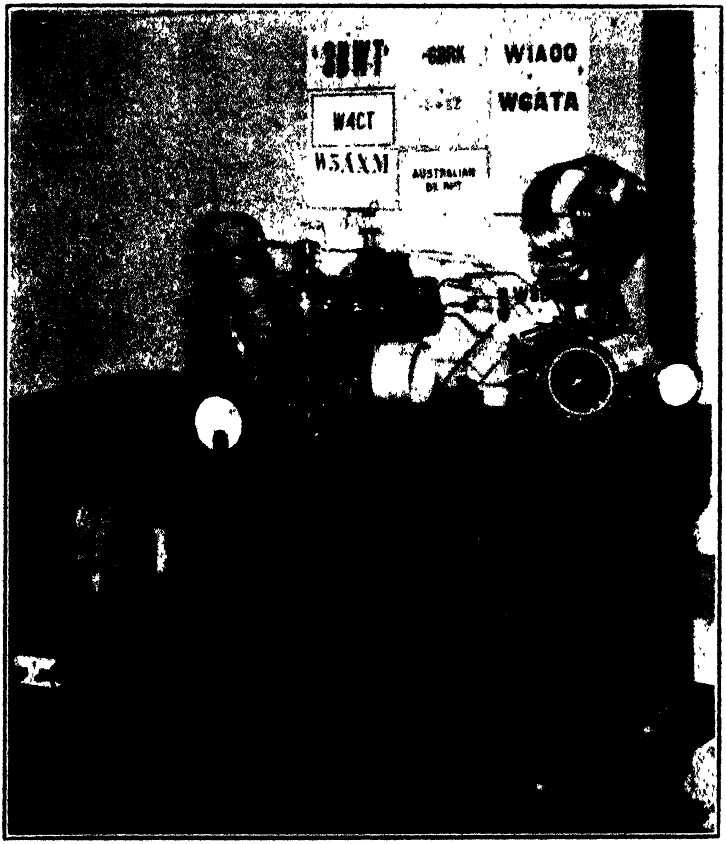

Washington State College short wave transmitter used by 7RL and employing two 75-watt tubes.

THE SHORT WAVE TRANSMITTER

by

David H. Sloan*

INTRODUCTION

In the early days of radio, or "wireless", it was the privilege of the amateur to roam at will through the radio spectrum so long as he kept out of the way of the commercial operators. When greater commercial use was made of radio, the amateur was directed by the government to confine his efforts to operations below 200 meters, or above 1,500 KC Further commercial developments both domestic and foreign, caused a part of this radio territory to be turned over to commercial use, with the result that the amateur was given somewhat narrower limits within which to work. At present (1929) the amateur transmitter is limited to operation in the following bands:

1715 - 2000 kc	14000 - 14400 kc
3500 - 4000	28000 - 30000
7000 - 7300	56000 - 60000
400000 - 401000	

Owing to the present development of short wave transmitters, some of these bands are more in use than others, with the result that considerable interference is experienced in the most used bands This is due to the type of transmitter used in the past, which, owing to its design, and to the fluctuating power supply common to many amateur stations, had the habit of permitting its radiated frequency to wander up and down the radio spectrum unnecessarily. The result was that a comparatively few transmitting stations filled the entire frequency

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assignments and for more stations to attempt to use the ether resulted only in serious interference, and frequent un-authorized excursions outside the allotted bands.

Thus has developed the need for a short-wave transmitter of more stable frequency characteristics which would use a limited frequency band in its operation and thereby reduce interference to a minimum The following report includes a variety of information which has been found useful in developing such radio transmitting stations It is intended to aid those who desire to understand more fully the details of operation of this type of equipment and to set forth some of the limitations and difficulties to be met in vacuum tube transmitter design Considerable familiarity with radio on the part of the reader is assumed.

THE OSCILLATOR

There are two common classes of vacuum tube oscillators, those which are controlled by quartz crystal resonators, and those which are self excited, the latter being by far the most numerous both in variety and in usage. The crystal type (provided it is properly built and adjusted) is unquestionably the best where stability of frequency is desired It is not to be recommended for general amateur use, however, because the frequency cannot be shifted at will, although for a station maintaining regular schedules this is a valuable feature The output of a crystal oscillator should never be forced to the maximum power obtainable because of danger of cracking the crystal, but should be limited by the maximum grid voltage which the crystal can deliver without frequency modulation, due to lower frequency vibrations caused by imperfect grinding and imperfections in the holder. This limit depends upon the individual crystal and its mounting.

In the discussion of the self excited vacuum tube it may be well to review some of the theory of such oscillators, in as non-mathematical a manner as possible. For simplicity either the Hartley or Colpitts circuits may be used, the former being selected because more people are familiar with it. Later, the relation between the more common circuits will be shown and their features noted.

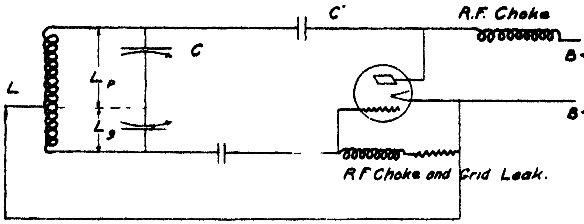

Figure 1

In the circuit of Figure 1, consider the tuned LC circuit and assume that the condenser C has received a charge due to closing some switch or to some other electrical disturbance in the circuit. Among other things this charge will pass from the positive to the negative side of C around through the inductance L, in the form of an electric current (or, better, an electron flow in the opposite direction) which in passing, sets up a magnetic field about L. When completely discharged to zero terminal volts, C can no longer force current through L, so the magnetic field about the latter collapses, generating a voltage in L which tends to keep the current flowing. This causes a charge to reappear in C, opposite in polarity to the first, and diminished by an amount determined by the energy lost in the process due to the current heating the conductors, and may also be diminished slightly by some of the energy being expended in radiating an electromagnetic wave into space. Each successive charge appearing on C is therefore smaller than the preceding one, the ratio of one charge to that following it being known as the decrement of that circuit.

The function of the vacuum tube is to take energy from the direct current supply and add it to the LC circuit at the proper time and in the proper direction to maintain each charge on C exactly equal to that preceding it. To do this the tube must supply as much energy as is lost in the resistance of the oscillating circuit.

Before examining the operation of the tube in supplying the oscillatory circuit, it may be well to recall a few of the characteristics of vacuum tubes themselves. The plate current increases with an increase in plate voltage faster than the direct relation given by Ohm's law, in fact it changes approximately as the 3/2 power of the voltage.

up to the saturation value of plate current, beyond which no great increase can be obtained unless the filament is made hotter to increase its electron emission. In ordinary triode oscillators using modern thoriated or oxide coated filaments this saturation current is seldom reached except at peaks of oscillations, at which times the extra electrons are readily supplied from the dense cloud of them surrounding the filament, the latter being restored while the oscillatory plate current is near its minimum.

The grid, being nearer the filament than the plate, can draw electrons away from the filament with a much smaller voltage than is required by the plate. Thus a small positive grid potential will cause a large increase in plate current, since the strongly positive plate will take a large share of the electrons started away from the filament by the grid. Similarly a negative grid is very influential in preventing electrons from starting toward the plate. The magnitude of this effect is called the amplification constant of the tube Thus, if a tube has an amplification factor of 8 a change of one volt in grid voltage will cause the same change in plate current as would result from a charge of 8 volts on the plate. This is expressed by (1)

$$8E_g = -E_p \qquad (1)$$

where E_g and E_p are pulsating, or rather oscillating voltages superimposed on the grid and plate, respectively

Although the grid voltage does not actually cause a new voltage $8E_g$ to appear in the plate circuit, the term $8E_g$ expresses the actual change in the internal resistance due to E_g in terms of a quantity which may be treated as a voltage when dealing with the current which will flow. E_g is in time phase with the additional voltage which would have to be applied to the plate to produce a given current change, had there been no E_g applied to the grid. Also it is 180° out of phase with (that is, opposite at every instant to) the actual voltage change which it causes at the plate terminal of the tube if the circuit is such as to keep the plate current constant.

Now consider the tube connected as in Figure 1, and the time to be when C is discharging with the grid side of C negative. Because of this discharge the grid is becoming less negative, and by its action

increasing the plate current which together with the choke coil causes the plate voltage to drop, which means that it is less positive, or more negative, and so by coupling through the blocking condenser, C′, it supplies electrons to C as well as on around through B to the power supply and back to the filament, thus increasing the rate of discharge of C. After C is discharged the inductance of coil L resists the decrease in the current through it and so tries to maintain the flow. This action of L also holds the voltage of the grid positive and so the tube continues to supply electrons to C, thus helping L to charge the condenser C in the reverse direction. During this time the grid is getting more positive and the plate current increasing and its voltage lowering, or becoming more negative. A point is finally reached where the cycle in this direction ceases and the reverse half cycle begins.

It may be shown that in a vacuum tube oscillator, as in most other sources of electrical energy, the maximum power output is obtained when the load impedance equals that of the generator. In the so-called low loss construction of the LC circuit an impedance much higher than that of the tube is obtained This apparently contradictory condition arises from the fact that when the LC circuit is made up with a very low resistance in L so that an oscillating current flows back and forth around the circuit L and C with very little loss we find that the opposition to flow of current from the tube through L and C in parallel becomes very high. (See any good text on alternating currents) So we make up a low loss oscillating circuit in order to get the desired high impedance in the tube circuit, and at the same time to reduce actual losses in the resistance of L to a minimum. The impedance of the LC circuit can now be made equal to that of the tube by decreasing the effective resistance of the LC circuit. This is usually accomplished by coupling L to the output or antenna circuit and thus increasing the output to the antenna. This permits more current to flow in both tube and antenna circuits and so gives the effect of a decreased impedance in LC. This necessity for matching impedance limits the output of the tube to a value equal to the power the tube itself can dissipate, even under the most ideal conditions. It is true that the efficiency of the oscillator can be increased beyond 50%, as a power converter, but only by

permitting distortion of the output. Balanced circuits using two or more tubes can be arranged to give 85% to 90% efficiency and maintain a good output wave shape, but a single tube is limited to less than 50% efficiency when required to deliver a nearly sinusoidal output wave form. This will be explained in greater detail under power amplifiers.

The most important feature in securing stability of frequency in self-excited oscillators is to be found in examining the expression for the generated frequency of the circuit which may be shown (Morecroft, p. 579) to be:

$$f = (1 + R' / R) / 2LC \qquad (2)$$

where f is frequency of generated oscillation.

R' is the effective series resistance of the LC circuit, that is, the resistance of L and its leads to C, including the effect of the energy delivered to the antenna.

R is filament to plate resistance within the tube.

L and C are constants of the tuned circuit, as in Figure 1.

An examination of this equation brings to light many interesting facts regarding the behavior of the circuit. A variation in the value of any term in the right hand member will affect the frequency. R', R, L, and C each have an interesting story to tell. It is desirable to have R' small and R large since they can not readily be made constant for all conditions of operation, and, of course, it is desirable to have each term remain as nearly constant as possible. Now for the ways and means of securing stability of frequency.

The load resistance R' represents the factor upon which the circuit is to perform its useful function of doing work, and cannot be made negligibly small and at the same time deliver power. Yet it is essential that its value be kept very small. The first thing to do is to eliminate all useless resistance. The part of the circuit where a very low resistance is most effective is right in the LC circuit. At the present time there is no equipment on the market designed to meet these needs adequately at 7000 kilocycles and higher. Even the accepted leader of all variable transmitting condensers has very small terminal screws, so placed that a low resistance stator connection

is difficult to make. A fairly satisfactory arrangement for this type of condenser is to bolt two of them together, back to back, and bond the frames with copper straps and the stators with a heavy copper plate, making connection to the four screws protruding from adjacent stator frames, to which are added several more heavy screws also binding the stators to the copper plate. This plate also supports a heavy mounting terminal for the inductance, the other end of which is attached to a similar terminal on the straps bonding together the condenser frames. The rotor connections were found to be the principal remaining source of resistance, as evidenced by their heating even with a moderate power oscillator. The problem of coil resistance is even more difficult. Of the many kinds of material tried for coils, hollow copper tubing was found to be the most satisfactory for moderate and low power oscillators, first, because of its low resistance, and second, because it can be very easily built into rigid self-supporting coils, and a suitable continuation of the tubing at each end forms low resistance leads to the condenser terminals. The turns should be wound with considerably less spacing than a distance equal to their diameter so as to increase the inductance per turn and hence use less length of tubing. Extremely close spacing increases eddy current losses considerably so that a space between turns of about half the diameter of the tubing is a fairly satisfactory value. With this low resistance type of construction, the circulating currents reach amazingly large values, so that heating becomes a real problem. Heavy copper ribbon, although harder to form into coils, is greatly to be preferred with an oscillator of 250 watts rating or greater. Strips an inch wide and thick enough to make a rigid coil, wound flatwise, give excellent results. With no external load, the full output of the tube goes into the LC circuit, and although the impedance of the latter is then quite high and the tube output reduced, considerable heat is developed. The oscillator cannot be loaded very heavily without seriously increasing R′, so one must choose between a large R′ with large power output and a lower value with an increased stability. A moderately large output will be desired, even at a reduction of stability, so the next thing to do is to reduce the factors which cause frequency changes in the less stable set.

Stability is affected in two ways when R′ is large. First, a given per cent change will cause a larger change in frequency than when

R′ is small, and second, the larger R′ is the greater is the effect of changing R caused by variation in the plate voltage. With an antenna which can not shift in the wind and change R′, and with a pure direct current plate supply voltage, the value of R′ can be made large, the power output of the tube greatly increased, and the ratio of useful watts to those heating the LC circuit greatly increased.

Notice this, however, that the above load can only be supplied at a constant frequency when the constants in the equation are **constant,** and that means R in particular, which changes inversely with the 2/3 power of the plate voltage. Hence a slight ripple in the d.c. supply voltage will change R and have a serious effect on the frequency if R′ is large. It is readily seen from this that to deliver a constant frequency to the load, the tube must be supplied with pure direct current, or else the load resistance must be negligibly small This pre-supposes that all values of L and C in the circuit are maintained constant

To meet the 1929 conditions fairly, the oscillator should be supplied with pure direct current and the load resistance made as small as economical.

A carrier wave caused by pure direct current supply unmodulated, is not pleasant to listen to for any length of time A good solution to the problem is to modulate it at a frequency which will be pleasing to the ear. But amplitude modulation should never be applied to the oscillator on the short wave bands. The frequency modulation which results is too great Refer again to equation (2) The smaller the values of L and C, (higher frequencies) the greater is the change in R′ or R, even though the L and C were maintained absolutely constant. Thus we see that the short wave transmitter is confronted by the problem which is not at all serious on the longer waves above 600 meters. While noticeable at broadcast frequencies it is not very serious, when the apparatus is not overloaded. But the same per cent change in generated frequency (appropriately termed "wobbulation" by QST) is roughly 10 to 20 times as great in kilocycles on the 7000 and 14000 kc bands. When one considers that the per cent "wobbulation" is from 10 to 100 times as great in the average amateur oscillator as in a good long wave commercial oscillator,

it is no wonder that the amateur bands are such a mess of interference. It is time for steps to be taken toward improving this condition.

A single self-excited oscillating tube can be made to give a sufficiently stable frequency when properly managed. From the foregoing discussion the relative effect of the different variable factors connected with the circuit may be compared. Each amateur must decide for himself which will suit his equipment best, either a constant plate voltage and normal load on the tube, or a voltage supply with a ripple, and the tube operating at greatly reduced load, in which latter case it may be well to use a power amplifier tube. In no case should the plate supply have more than 15% to 20% ripple if the frequency is to remain reasonably constant throughout one cycle of the ripple.

The next problem is that of the ratio of L to C in the oscillator circuit. There are arguments in favor of a high ratio, as well as favoring a low one. The vacuum tube is primarily a voltage operated device, and as such it is much easier to obtain high efficiency with a high L/C ratio, because the inductive reactance increases nearly with the square of the number of turns and requires a wattless current to give a reactance drop or voltage across it, whereas the resistance increases only slightly faster than the first power of the number of turns at radio frequencies, and it is the resistance which wastes power. This accounts for the increased heating of the LC circuit when L is small, for the larger current which must then flow to give an impedance drop to suit the tube, meets with a greater ratio of resistance to reactance, in spite of the fact that the resistance has been reduced.

But we are more concerned with the frequency stability than with the electrical efficiency of the circuit. Equation (2) indicates unquestionably better stability for the lower R′ circuit arrangement, other things being equal.

The effect of L and C changes due to external causes, such as tube and apparatus heating, has been wrongly interpreted in many instances. When a transmitter warms up, the frequency usually decreases, yet tube heating, which reduces its effective capacity would cause the frequency to increase. The heating of the inductance, which

causes a slight increase in diameter with the consequent rise in inductance and lowering of frequency, may be much more than enough to offset the rise due to decreased capacity. In the circuit with high L/C ratio where heating is greater, one would expect a large decrease in frequency, but such is not usually the case, fortunately, for the heating of the condenser end plates and plate supports reduces the capacity of the circuit enough to compensate, or even cause a rise, in frequency. Here again is room for experiment by each individual station builder, to find out how best to use his available apparatus

THE POWER AMPLIFIER

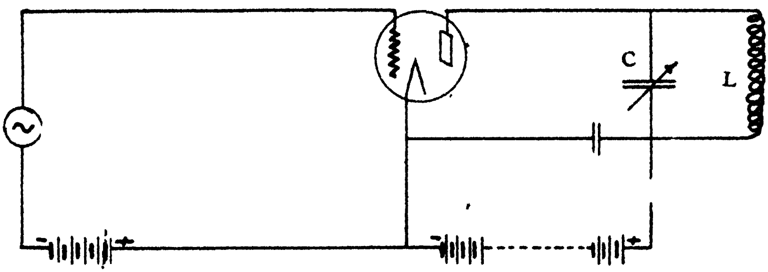

Figure 2

The power amplifier is by far the most suitable arrangement for the amateur who desires more than a few watts output, yet has insufficient direct current for the plate supply. It is also the ideal way to get a low note ripple in the output frequency without causing that frequency to shift by more than the low modulating frequency, or in other words, to obtain the ripple without "wobbulation." The best feature, however, is the great increase in power output obtainable from a given tube, being from two to five times as great as for that tube acting as an oscillator.

The tuned plate circuit of a power amplifier tube may be one with a high L/C ratio, to obtain better tube efficiency, and yet this circuit will have very little effect on the frequency of the oscillator, which should be built with great care to obtain stability.

It may be well to review briefly the action of an amplifier, keeping in mind its application to radio frequencies. Let us assume that

in all cases the output circuit impedance is made equal to, at least within 30%, of the tube impedance.

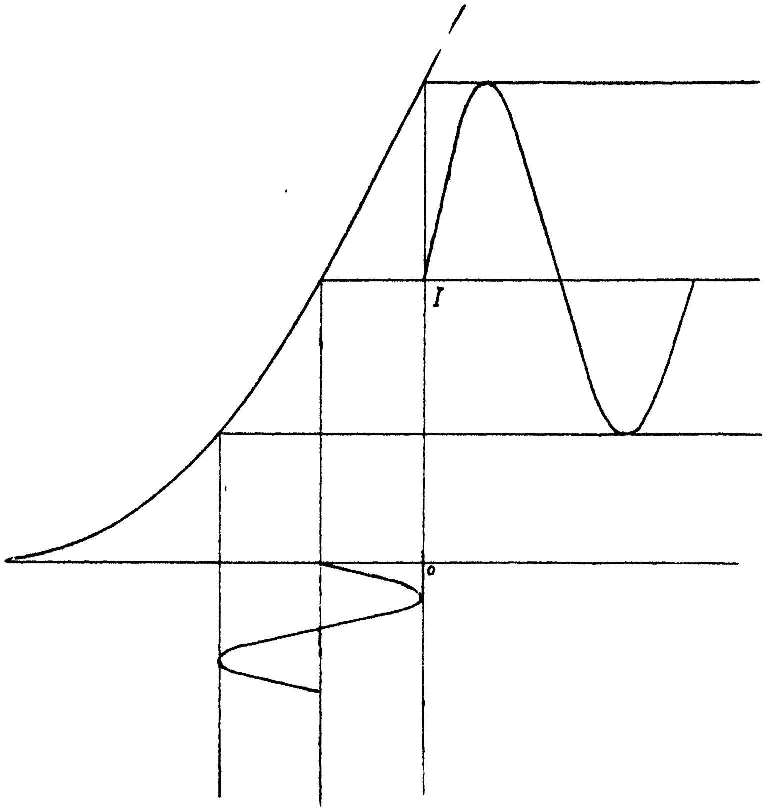

Figure 3

The familiar representation given in Figure 3 shows the nearly ideal functioning of a tube as a distortionless amplifier. But the trouble is that only a power output of less than 10% of the rated watts plate dissipation of the tube may be obtained before the distortion becomes noticeable. Only with an infinitely small output can the ordinary triode be called 100% distortionless. For practical purposes it has been found that 5% second harmonic distortion may be tolerated in good audio amplification. On this basis one may expect an output equal to approximately 20% of the plate dissipation rating.

Except in certain phone combinations to be discussed later, this type of amplification has no practical value in amateur transmission, because of its low efficiency.

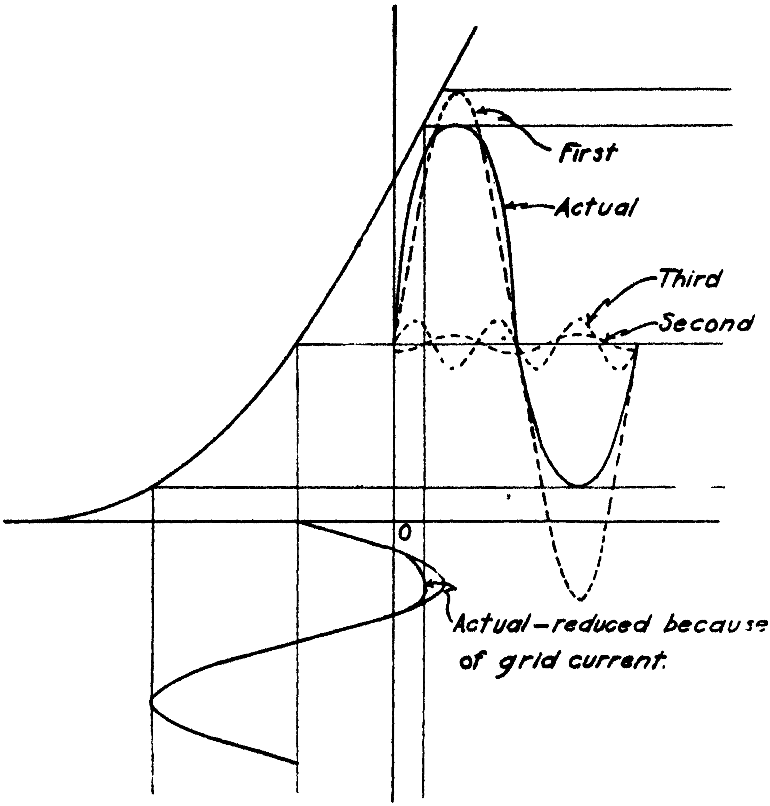

Figure 4

Passing to the condition shown in Figure 4, which shows the introduction of a third harmonic in the output, we find another interesting but impractical radio frequency amplifier, for it, too, has a relatively low efficiency. The adjustment for Figure 4 may be obtained most easily by reducing the plate and grid battery voltage by about 25%, so that the alternating grid potential will cause the grid to swing negative past the lower curve in the characteristic curve, with a lessening in the plate current decrease at the negative

peak of the cycle. The grid now actually swings past the zero value and slightly positive, but the grid current which flows under these conditions causes a voltage drop across the impedance of the exciting current which prevents the grid becoming as positive as the applied voltages would otherwise make it. The resultant flattening of both the positive and negative peaks of the output alternating current is the equivalent of adding to this current one of triple the frequency, as may be seen from Figure 4. This method is useful for tripling the frequency of the supplied e. m. f., where power output efficiency is of minor importance, but here again, the amateur, in search of more efficient methods of utilizing his small outlay of equipment, may resort to another type of distortion for second as well as third harmonic amplification It must be remembered in this discussion of 1st, 2nd, and 3rd harmonic amplification that there are also present several hundred higher harmonics of a very much smaller magnitude, which are accounted for mathematically by showing that they are all sine waves, adding up to compose the actual irregular wave generated by the tube. When the tube is forced considerably less than indicated in Figure 3, all harmonics higher than about the fifth or seventh are negligible, but when operated as amateurs are wont to do, the number noticeable may easily be increased tenfold. It is well, then, to have a fair idea of the fundamental processes in order to emphasize the particular harmonic desired in a given set-up of apparatus.

With the grid biased almost enough to cut off the plate current, and with grid excitation just low enough not to swing the grid positive and draw grid current, a somewhat more efficient distortion amplifier than the foregoing types is obtained, giving about one-fourth as many watts second harmonic as the rated plate dissipation watts. All of these amplifiers, characterized by the grid excitation shown in Figures 3, 4, and 5, are useful only for experimental radio frequency power amplifiers in which it is desired to study the behavior of the tube and circuits, with a view toward an understanding of what takes place in the more useful power amplifier arrangement in which a large grid current is drawn, even though the tube is biased beyond the normal plate current cut-off.

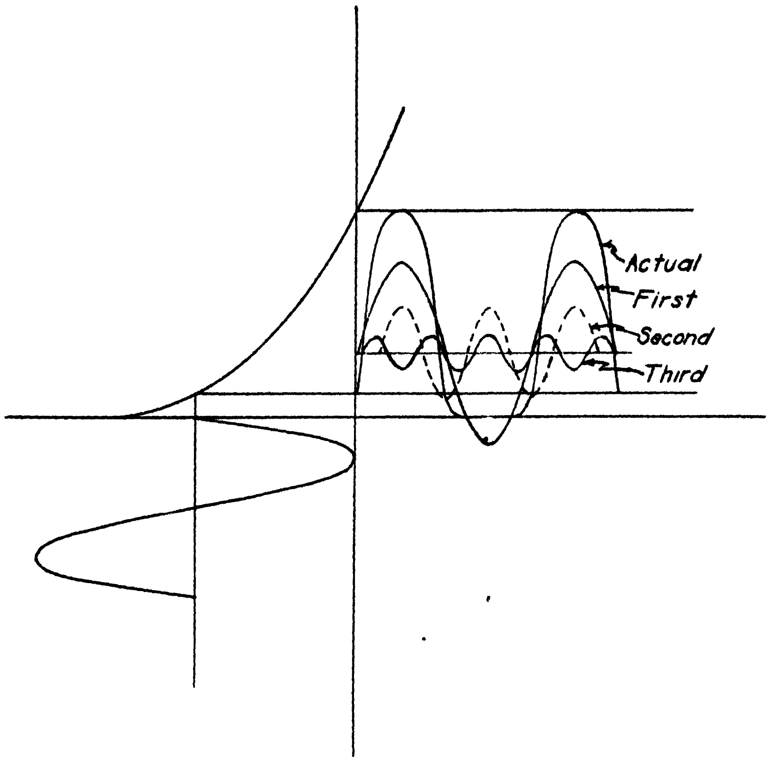

Figure 5

POWER AMPLIFIER DRAWING GRID CURRENT

It is in this class that the practical power amplifiers belong, for by this method relatively large outputs may be obtained, with efficiencies ranging from 60% to 85%. It is interesting to note that where plate heating is the factor determining maximum output of the tube, the output at 85% efficiency can safely be almost five times as great as at 50% efficiency.

For this use the filament must be able to supply sufficient emission to give the maximum plate current which the tube will draw with the grid strongly positive. The static characteristic of the tube

will be similar to Figure 6, curve S, with the most valuable section lying between a and b. Of course, the actual values for such a curve can not be measured because such currents would destroy the tube if allowed to flow more than momentarily, and are very hard to obtain even with an oscillograph. The dynamic characteristic, with a load impedance approximately equal to that of the plate, will give a curve, the values of which are fortunately not so destructive to the tube, and permit the tube to be operated with the currents more like those of curve D, Figure 6. The slope of the plate current then falls

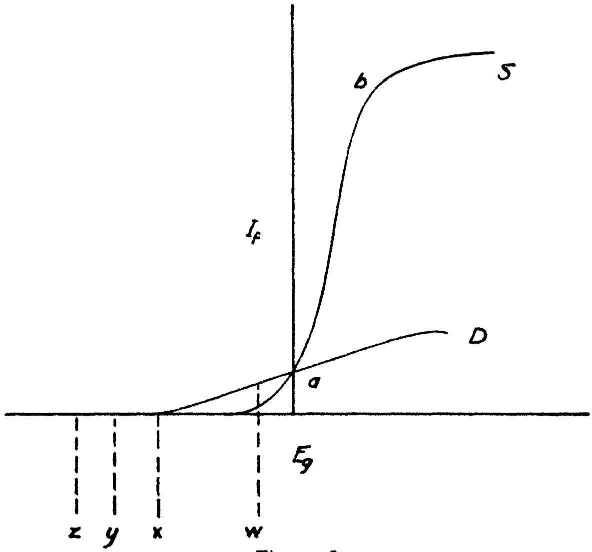

Figure 6

off rapidly when the plate voltage is reduced (by the drop across the load impedance L, Figure 2), to a value near that of the grid voltage The plate LC or tank circuit should be tuned very close to the frequency being amplified, and in this condition for the usual changes in plate current it will act almost like a series resistance in the plate circuit, yet retaining the power of the inductance to generate counter electro-motive forces opposing current changes in the plate circuit. A large positive grid voltage suddenly applied can reduce the plate voltage to zero or even make it negative because of the impedance in the plate supply circuit, and vice versa Suddenly swinging this

positive grid voltage to a large negative value causes a large decrease in the abnormally high plate current resulting in the plate rising to a very high positive potential. These large swings in plate voltage, caused by swinging the grid from very large negative to large positive values, allow very large impulses of current to be set up in the tuned plate circuit.

To raise the grid to a positive potential in spite of the negative electrons which immediately begin flowing to it (and which tend to cause it to remain negative), requires power in large amounts, compared with that needed to merely change the instantaneous potential of a negative grid which at no time draws much current, as in Figures 3 and 5. These latter require only a capacity charging current. Figure 4 is a case of a grid excitation source with voltage sufficient to make the grid positive but without power enough in this source to drive the grid very far positive against the effect of the grid current drawn from the space charge.

For fundamental (or first harmonic) amplification, the grid may be biased to some value W, Figure 6, which presents a long dynamic curve toward either side of W. The more positive this point the greater is the plate heating for the same power output, and the more negative the point W is taken, the smaller is the maximum power output obtainable with excitation great enough to lower the plate voltage to a value similar to that of the most positive grid potential Since the output wave is distorted, giving undesirable harmonics, when the plate voltage is forced lower than the grid voltage, it is seldom desirable to excite the grid strongly enough to cause this unnecessary lowering of plate voltage.

The values of voltage are hard to determine beforehand and much harder to measure. The best way to adjust the power amplifier is to keep in mind the effect of each voltage and to vary the bias and excitation over a considerable range, and select a value giving the greatest tank circuit current with minimum input and plate heating and be sure the value selected is one which will not melt the grid. The grid should not be run at more than a dull red heat to avoid a large secondary emission of electrons from it.

To apply this type of amplification to second and third harmonic amplification, the scheme of Figures 5 and 6 may be used. Figure

5 is suited only to second harmonic amplification, and then only when the excitation is powerful enough to drive the grid to large positive values without the effect of Figure 4. Remember that these must be dynamic and not static characteristic curves. In Figure 6, for second harmonic amplification, the bias is put at X, and excitation increased accordingly. To obtain an almost pure second harmonic, the bias may be increased to some point Y, at which plate current can flow only one-half of each positive half cycle, or one-fourth of a cycle at the fundamental frequency which means that the second harmonic frequency current in the plate circuit flows only one half cycle in each four half cycles, the oscillating current in LC being maintained the other three half cycles by having a tank circuit with low decrement tuned to the second harmonic. By increasing the bias to Z, a value will be found which will energize a tank circuit tuned to the third harmonic only once in six half cycles. Efficiencies of 30% to 45% may be obtained with this type of harmonic amplifier.

The self excited oscillator may be considered as a power amplifier circuit whose grid excitation is obtained from a circuit coupled to the output of the amplifier. Keeping this in mind the adjustment of an oscillator and its biasing grid leak and condenser can be regulated to give better efficiency than is obtained in many amateur stations. This becomes especially important with the new requirements by law concerning the stability of the output, to meet which the oscillator is handicapped by a lower L/C ratio circuit and by a reduced antenna load or looser antenna coupling, making a very small gain in efficiency worth while.

Concerning the value of grid and plate alternating voltages in a self excited oscillator, there is apparently a misunderstanding by some of the amateurs which may be explained away in this manner. Take the Hartley circuit of Figure 1, with a double stator condenser for symmetry of diagram. The plate section of the inductance, L_p, with its capacity may be considered as the tuned output, and L_g with its capacity as the tuned input to the tube. The actual frequency will be that of the combined total L and C, since they are built as one circuit, L_p and L_g being closely coupled. The impedance of L_p and L_g with their respective capacities may be seen more clearly in the Armstrong tuned grid and plate circuit where the two cir-

cuits are entirely removed from each other, the grid circuit receiving its power from the plate output tank circuit only by capacitive coupling through the tube. This separation of L_p and L_g is seen in the Meissner circuit also, where they are coupled only through the load.

The location of the filament tap on L is not a case of trying to find a voltage node on L, because this node must be wherever the tap is placed. It is a case of changing the ratio of grid to plate voltages, with L acting as an auto-transformer. When the proper ratio of L_p to L_g is obtained to give the proper bias for the grid leak and condenser used, then try other values of the leak and condenser, and find the best new position of the filament tap on L. Usually one knows beforehand the size of leak to use with the tube, and the size grid condenser for that tube for the frequency desired. A value of 250 to 1000 mmf. for the common tubes is suitable for all the popular short wave channels in amateur use, and this value is not at all critical. The leak is a little more critical for the best bias. Then it is chiefly a case of setting the filament tap on L for the best voltage ratio in any particular set. The value of this ratio changes slightly with the load on the LC circuit, and the position along L to obtain a given ratio changes slightly with different methods of coupling the load to the LC circuit. The best adjustment therefore is a matter of trial only. When these ratios are correct at one plate voltage they will hold over a wide range of plate voltages because E_g and the bias due to the grid leak will increase and decrease the right amount as E_p changes. E_p and E_g may be average, r.m.s, or peak values of the alternating components. This is where the power amplifier is at a disadvantage, since there is usually nothing to change the excitation or the bias as the plate voltage is changed. Normal usage, however, does not require a change in this plate voltage.

PUSH-PULL AMPLIFIERS AND OSCILLATORS

To eliminate second harmonic distortion either in audio amplifiers, radio power amplifiers, or in oscillators, use is made of the push-pull circuit to provide a symmetrical output; one half cycle being the exact shape but opposite in polarity to the one preceding or following

it. The symmetrical wave, no matter how greatly it differs from a sine wave, may have odd harmonic components. Since a vacuum tube can be forced to greater voltage variations before the third harmonic is troublesome than it can before the second begins to manifest itself, as seen in Figures 4 and 5, each tube in the push-pull circuit may be run at a higher output than that tube could have been alone. Thus in an amplifier not limited by breakdown voltage, the output can be increased much more than double by using two tubes in the push-pull arrangement. Although a high L to C ratio is quite desirable in the output of an ordinary radio frequency amplifier, it is much more important in a push-pull circuit since only one-half of the voltage drop across the tank circuit is available for each of the tubes working into it This same consideration acts against the desirability of a push-pull oscillator for an increase in output, because the resulting high L to C ratio needed to obtain power causes instability of frequency, even though the tube capacities are in series. However, an oscillator of this type will give a very pure wave shape, if the supply voltage and load resistance can be held constant. The Mesny* circuit is merely a push-pull arrangement of the tuned grid and plate, and of the Hartley circuit Another combination may be had by taking two Hartley oscillators, and exciting the grid of one from the plate circuit of the other, and the grid of the latter being excited from the plate circuit of the former. This latter arrangement, while permitting the operation of two or even three or more tubes in series, and thus getting down to a slightly shorter wave length than with one tube, does not have the balancing effect found in the Mesny arrangement, although the latter will not go to such a short wave length. The Mesny does not eliminate chokes and blocking condensers, however, and in this respect it is to be preferred to the regular series operation

POWER SUPPLY

It is clear that the vacuum tube cannot generate a constant frequency over a range of plate voltages This does not mean merely modulation of the generated frequency by adding and subtracting the supply ripple frequency but an actual change in generated fre-

* Mesny, R.; see page 107, Radio Engineering Principles, by Lauer and Brown

quency for the different voltages caused by the ripple. Proper circuit design and adjustment can be made to greatly minimize this tendency toward frequency modulation or "wobbulation."

In any oscillator which is to be used for telegraph work it is still desirable to have a pure direct current plate supply, and add the side bands so popular for steady copying by modulating the pure cw in a power amplifier stage.

To obtain the pure unmodulated direct current there are many types of rectifiers available, as well as motor generators. For low voltages, up to 1000 volts, the UX281 kenotron is probably the best, while for higher voltages and higher power the mercury arc rectifier is very desirable because of its low voltage drop. The starting and keep alive circuits are very bothersome, however. A new hot cathode mercury vapor tube is available for amateur use, in two sizes, a pair of the smaller being large enough to operate a 250 watt tube at nearly normal output, delivering 600 milliamperes at 1500 volts, or 400 milliamperes at 1750 volts, depending upon the filter circuit. A pair of the larger tubes will supply about five amperes at 4000 volts. These tubes have a drop of only four or five volts from cathode to anode, and have a very high over-all efficiency. It would seem that this is to be the answer to the long demand for a sturdy and efficient rectifier.

THE ANTENNA

A great deal has been written about a great many variations of the open Hertzian resonator as a radiator of electro-magnetic waves. There are a few points which have received little or no attention, although they are involved in most antenna problems. A much better understanding may be had by considering first the antenna as a circuit in which wave transmission and reflection phenomena occur, and then consider what is essential to the radiation of the energy.

Take the case of an infinitely long insulated straight conductor. If a charge is put on one end of this wire, its effect will be to raise the potential of the wire at that end. The electric field about this charged end tends to raise the potential of nearby objects. This effect is greatest on adjacent portions of the wire, and a wave travels out

along the wire with a speed nearly equal to that of light, raising the potential at each successive point. The energy by which the charge is carried along the wire is stored in space as an electric and magnetic field. The magnitude of the charge is reduced or attenuated as it progresses, due to resistance losses and leakage, but it stores most of its energy in "fresh ether" around the wire continuously and expands both magnetic and electric fields as it travels out along the wire. If the wire has an end as most antennae do, the charge stops its travel on reaching the end and reversal begins. The two fields can not collapse completely on this rapid reversal but the electric charge and its field are reflected back along the wire with increased values. The interlocking of electric and magnetic fields makes it possible for a portion of the energy stored in the space around the antenna to maintain itself as a travelling wave much as an oscillating float can send out surface waves on water. These waves absorb energy from the oscillator and never return, but travel away until their energy is all lost in various absorbing media or receiving circuits, useful or otherwise.*

Using a pair of insulated wires in the above experiment, opposite charges being impressed on each, the wave would travel to the end, and upon being reflected the interlinking of fields would prevent appreciable radiation, really trading energy from one wire to the other at the reversal. However, it a transformer of the same impedance as the line were placed at the end of the line the opposite charges would flow into the transformer just as into a continuation of the line, and with no reflection possible the radiation would in this instance also be negligible, but energy would be taken into a secondary circuit of the transformer.

A line in which no reflections occur from the ends has an exponentially decreasing voltage along the line as the distance increases from the sending end. However, if this insulated line has both ends insulated, so the energy upon reaching an end is reflected back, and another charge is added in phase with the reflected one when it gets back to the origin, the reflection from end to end may be built up at this resonant frequency. The line then becomes one type of Hertzian

See Richtmyer, Introduction to Modern Physics, for a rigorous statement.

antenna, voltage excited at one end. Radiation now takes a well defined character, the electrostatic component reaching a maximum at the reversal of the charge upon reaching an end, and the electromagnetic component reaching its maximum 90° later as the current at the voltage nodes passes through its maximum. Standing waves are now present along the wire, the voltage nodes never rising in potential as each point along the wire does with travelling waves, because the periodic oscillation of the charge and its fields tends to make one voltage antinode as much positive with respect to space as the next antinode is negative, thereby permitting the voltage node to be a point never changing its potential with respect to space.

If now the secondary of the transformer terminating the two-wire transmission line be inserted at the voltage node of an open antenna such as the one just described this antenna may receive its energy periodically, in phase with the current at this point, 90° out of phase with the time of maximum energy input by the voltage feed at the end of the line. Energy may be given to the transmission line by a similar transformer whose secondary impedance matches that of the line, and whose primary receives its power from a vacuum tube oscillator or amplifier circuit.

The natural or surge impedance of a two-wire transmission line is easily calculated from the relation $Z_o = L/C$, where L and C are in henries and farads per unit length of line. Since these qualities increase directly with length of line, the value of surge impedance remains constant for any length, being determined only by wire diameter and spacing. For the ordinary two-wire line, No. 10 to No. 14, spaced about 10 to 18 inches, this value of Z_o lies between 500 and 700 ohms A coil of this impedance is rather large sized, for broadcast or amateur frequencies, so a line of lower impedance is desirable. It was found that an 80-foot twisted pair of No. 8 rubber covered wire had a surge impedance of 28 ohms. A transformer to match this was easily built, three turns of a 13″ diameter antenna loading coil used as an auto transformer being about right at 760 kc. With this arrangement the transfer of energy from a 500 watt power amplifier tank circuit through 80 feet of transmission line to the antenna was as good as if the antenna were brought into the station and conductively or inductively coupled to the tank circuit.

The dielectric losses in the insulation were negligible, since a potential of less than 100 volts existed between the wires of the line.

In view of the success of this line at 760 kc, one was constructed for 15,000 kc or 20 meters, and was made 280 feet long, connected to a four-turn inductance three inches in diameter, for coupling the line to the load conductively and to the oscillator inductively, Figure 7. With a constant output of 500 watts from the oscillator-power amplifier the power in the antenna, coupled in the regular inductive fashion, was 500 watts, as compared to 375 watts when transmitted through the line. This represents a loss of 25% of the energy, chiefly as a dielectric loss, in the transmission line.

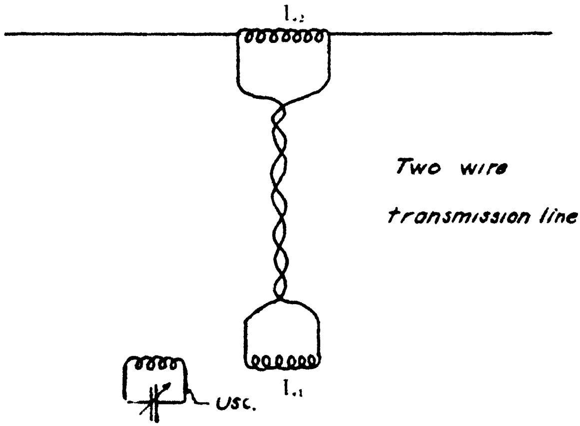

Figure 7

In consideration of the ease of installation of this twisted pair, and its non-radiating characteristics, and independence from surrounding objects, it may be found of value when the usual methods are unsatisfactory for connecting the transmitter to the antenna because of a poor location of the apparatus. Its only objectionable feature is the inability to cover a wide range of frequencies such as harmonic wave bands, but it will easily cover any one of the short wave bands without change of adjustment. Separate systems may be provided for each wave band, if several are desired.

Another system, suggested by the above, involves the so-called voltage feed Hertzian antenna, the adjustments of which are commonly very difficult to make.

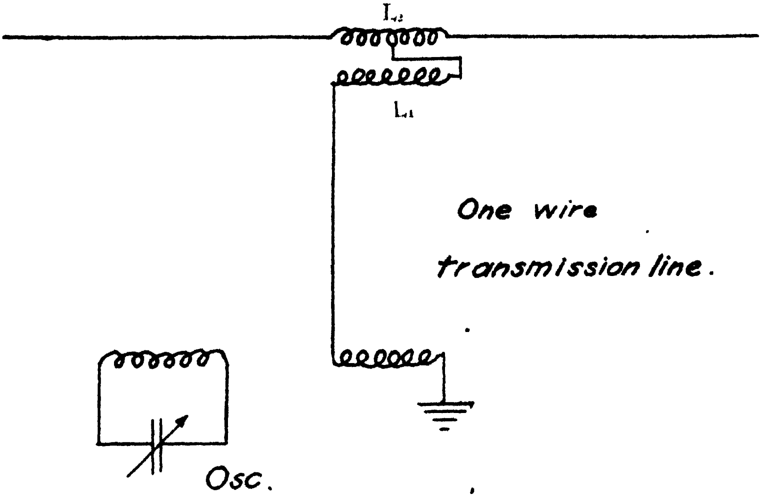

Figure 8

The impedance of a two-wire line is determined by the L and C per unit length, $Z_0 = \sqrt{L/C}$. This is not so easily applied to a single wire line, in which the L increases by an increasing increment with each unit increase in length, and the C increases by a decreasing amount for each additional unit length. Thus the value of Z_0 for a No. 12 wire at radio frequencies varies in somewhat the following manner:

Length	Natural impedance
1 cm.	132 ohms
10 cm	274 ohms
100 cm.	371 ohms
10 meters	550 ohms
100 meters	690 ohms

It will be noticed that for all the usual feeder lengths, which will be between 10 and 100 meters long, the impedance changes only a small amount. With a line 10 meters long one may with a great amount of patience find a point on a particular Hertz antenna which

will have an impedance to the feeding circuit of 550 ohms. Another way is to try the arrangement of Figure 8, where the impedance of L_1 is approximately 550 ohms at the resonant frequency of the Hertz antenna, and L_2 is just large enough to couple the desired amount of energy from L_1 into the antenna circuit. This transmission line will be practically non-radiating and its impedance will be practically constant even when swinging violently, and therefore will cause almost zero variation in power output, and generated frequency.

Most stations desire a single antenna for several harmonic wave bands. The current feed Hertzian system with standing waves, or the voltage feed "Zeppelin" antenna with a similar feed line but one-fourth wave-length longer or shorter than for the Hertzian antenna are very popular and have several commendable features. Both of these systems are long, harmonically resonant antennas, of which a portion has been folded back upon itself at the proper place to have the field of one wire in the "transmission" line cancel the major portion of the field of the other wire.

Where strong radiation from that portion of these systems near the transmitter is not objectionable, a much simpler method may be used, by not "folding up" a portion and using that to couple to the oscillator, but to couple the free end of the antenna, which will be a voltage antinode at all harmonics, directly to the "live" end of the output tank circuit of the transmitter, which will always have the desired voltage and impedance for matching the free end of the antenna If a push-pull power amplifier is used so that both ends of the inductance are at high radio frequency potential to ground, coupling to one end will cause the unloaded half of the circuit to transfer energy to the loaded portion, as in an auto transformer.

In the calculation of the length of wire which will resonate at a given frequency, there is some discussion as to what fraction of a wavelength the wire should be. Perhaps the following will help to eliminate some of the unnecessary confusion and arguments.

For a wire resonant at its fundamental frequency as in Figure 9 (a), let it be assumed that for a given installation the length of the wire is found to be .44 times the wavelength. Then for (a) the ratio

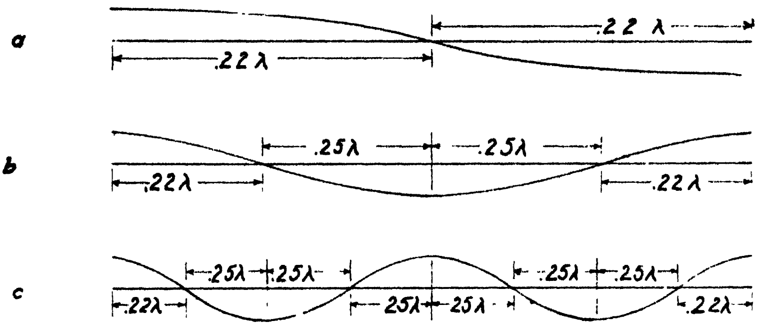

Figure 9

of wire length to wavelength of the standing wave upon it is .88, for (b) it is .94, and for (c) it is .97. The difference found between the end segments and those intermediate is due to the fact that the charge can travel faster along the sections of the wire which are terminated at both ends by more wire, in which case the section is terminated by matched impedances, with no tendency to reverse the direction of flow. The end sections for which one end of each is open, have a considerably increased capacity due to the objects beyond the end of the wire, such as guy wires, towers, etc. This results in a quite different electrostatic field distribution and a lowered velocity of travel along the wire in the end sections. The charge travels with nearly the velocity of light along the wire between x and y of Figure 9 (b) and (c), while it seems to travel with an average velocity only .88 as great in the end sections, though this correction factor varies with the local conditions.

For this reason a wire resonant at 80 meters will have its harmonics at about 37.5 and 18.3 meters. As the number of harmonics increases, the wavelength approaches exact harmonics of 75 meters, the actual wavelength of this much wire if terminated at each end by an infinite length of wire rather than by an insulator

RECEIVING CIRCUITS

Such a wealth of information on this subject has been published in QST that it is hardly necessary to dwell upon it here. However, a few words might not be amiss.

The single regenerative detector with plug in coils and tuning condensers, built with the usual low-loss construction, will probably be the most popular arrangement for some time to come. With the increased stability of transmitter frequencies one stage of tuned audio amplification seems to have great possibilities for increasing selectivity. A sharply tuned circuit with high ratio of L to C, adjustable to several audio frequencies, as the plate impedance for coupling four element amplifier into a 201A or 112A tube for second audio stage, gives very good audio frequency selective amplification.

The use of an untuned shield grid tube for coupling the antenna to the detector tuning circuit is valuable for isolating the effect of tuning in one circuit upon that of the other, and prevents radiation As commonly used, the radio frequency amplifier provides only a little gain in signal strength, and this in a less desirable form than might be had by the use of a tuned audio stage. However, with proper precautions the screen grid tube can be made to give a large gain on 20 or even 10 meters although it is doubtful whether or not this gain is really useful in increasing the range of the receiver.

When using a UX222 or the A.C. model screen grid tube as a radio frequency amplifier in any circuit, the following precautions are necessary for amplification at high frequencies, due to the impedance drops along the leads within the tubes. Put a by-pass condenser, .001 to .006, from the screen grid terminal and from the positive end of the filament to the filament minus. It doesn't matter which end is plus or minus. These are best strapped to the base of the tube itself The filament minus is then by-passed to ground, as near to the tube terminal as the connection can be made. Experimental tubes have been made with the screen grid lead out the side of the tube, for a more direct by-pass to ground. A close fitting metal cover around the tube, also grounded, reduces the feed back through the tube still further. Put this tube, shield, and by-pass condensers in the circuit shield enclosing the output circuit of the tube. The input circuit is outside of this shield, leading to the shield grid terminal on the top of the tube by a short direct lead, also preferably shielded. This reduces the energy transferred from the plate back to the grid circuit and permits very great amplification even at ten or twenty meters

When thus shielded, a tuned input may be used to advantage with the conventional one stage radio frequency and oscillating detector with the tuning of one circuit absolutely independent of that of the other. Of course it is necessary to put radio frequency chokes and by-pass condensers in each battery lead and the output, which have wires passing through the shielding.

The author wishes to thank the members of the electrical engineering faculty for their valuable assistance in collecting this information, and is greatly indebted to Mr. H. V. Carpenter, Dean of the College of Engineering, the State College of Washington, for his timely suggestions and valuable assistance in the preparation of this material.

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 12 October, 1929 No. 5

The Elasticity of Concrete

by

H. H. Langdon

ENGINEERING BULLETIN NO. 30

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

APRIL, 1930

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "**to further the application of the principles of physical science to industrial pursuits.**" The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

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THE ELASTICITY OF CONCRETE

by H. H. Langdon

INTRODUCTION

Concrete is one of the leading materials of construction. It is therefore essential that we know accurately the physical properties of concrete in order that we can design our structures for the greatest safety and the maximum economy.

The stress-strain relationships for concrete have been the object of a great deal of investigation by many experimenters, and yet at the present time there seems to be a difference of opinion among these investigators as to the elastic properties of concrete.

The writer, in charge of the Materials Testing Laboratory at the State College of Washington, while conducting routine and special tests on concrete specimens, has been able to accumulate sufficient data to support the premise that concrete does possess elasticity in the same sense that steel possesses elasticity.

The data and conclusions herein presented should prove of especial value for comparative purposes since they were obtained by the use of a new type of compressometer, (described later) not used heretofore by any other investigator.

THE SOURCE OF THE DATA PRESENTED

The Materials Testing Laboratory at the State College of Washington has for its purpose the following functions:

1. The instruction of students in engineering.
2. The testing of materials that go into and result from Campus construction.

3. The testing of materials that may, from time to time, be sent in by individuals, corporations, and municipalities of the State.

4. To conduct whatever research that time, equipment, and materials will allow.

It has been the aim of those in charge of the laboratory to make the most of each opportunity, and therefore, during the past year data have been accumulated for all tests made during the routine of carrying out the above functions of the laboratory.

In studying the data and results herein presented the reader should keep in mind that in all cases, except one, the cylinders were made and tested for purposes other than for the stress-strain relations which they might exhibit. For instance, the cylinders made and tested by students were for the purposes of instruction and practice in concrete design under the water-cement ratio method. This is also true of the cylinders sent in from Campus construction jobs and from individuals and municipalities. The only case of cylinders made for the stress-strain relation which they might show is reported under File Nos. 24 to 34 in Table 1.

SCOPE OF THE DATA PRESENTED

The data presented in Table 1 can be divided into three distinct groups.

First: Data taken from the laboratory mixes, which were made and tested under laboratory conditions. They had for their purpose the design of concrete to meet certain specifications and the economic grading of aggregates; for example, the design of a good concrete mixture for a specific campus construction job. Again, studies have been made in the laboratory in regard to economic grading of fine and coarse aggregates. The stress-strain relations of all the cylinders made for these purposes are listed under "Lab." in Table 1.

Second: Results of student instruction. This work was done entirely under the guidance of their instructor. The students

were divided into groups of three or four members. Some fifteen of such groups designed concrete to give a predetermined strength using the "Trial Method" as advocated by the Portland Cement Association. After the students became familiar with the design method, each laboratory section constructed a large concrete beam and at the same time made at least four cylinders for testing. This work is listed under "Stud." in Table 1.

Third: Cylinders made in the field in actual construction jobs such as city pavements, large building jobs on the State College Campus, and elsewhere. The laboratory had no control in some of these cases and only partial control in the case of Campus construction. In some cases then the mix and aggregate data are lacking. These cylinders are designated "Field" in Table 1 and constitute a majority of the cylinders tested.

APPARATUS AND METHOD

This bulletin is primarily concerned with the stress-strain relationship. The values of design and method of control and curing are not known in all cases. This is particularly true of the cylinders sent in from the "Field." Those made and designed in the laboratory, designated by "Lab." and "Stud." in Table 1, were made and designed as nearly as local conditions would permit in accordance with the procedure outlined by the American Society for Testing Materials. In the latter cases the curing was accomplished in damp sand at room temperature. The cylinders were tested damp unless otherwise noted.

Two testing machines were used, each having a capacity of 200,000 pounds, but operating on different principles. One was a hydraulic type with beam-weighing, the scale marked with 20-pound divisions. The upper head only was spherically seated. The other machine was of the screw type with 10-pound divisions on the scale This machine was not equipped with spherical heads for the first of the series of tests made on this testing machine. The cylinders tested without the use of spherical heads were capped with plaster of Paris in place and allowed to harden for at least two hours.

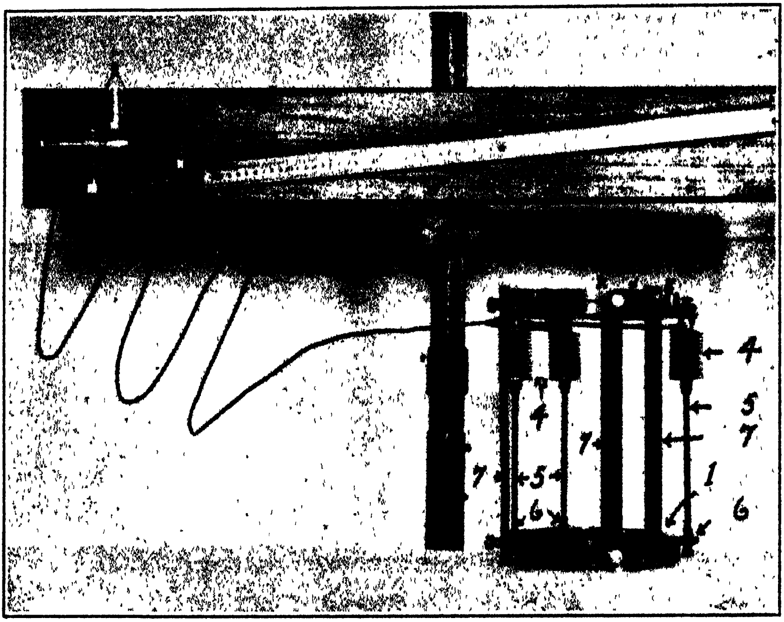

Figure 1. View of the Complete Instrument as Constructed for Compression Tests of Concrete Cylinders.

Later it was felt that errors were present due to the plaster of Paris capping with fixed heads. A spherical head was obtained and the cylinders which came from the field were capped with a mortar of 1-2 Lumnite cement and sand at least 24 hours before testing. The curing of the Lumnite mortar was very carefully done and better results were obtained. It was felt that the plaster of Paris failed before the elastic limit was passed in the concrete cylinder in the case of high strength concrete. This failure caused the fixed head to bear unequally on the concrete cylinder which in turn gave eccentric loadings. Erratic values of the elastic limit point resulted, due to the development of diagonal planes of rupture near the ends.

The screw machine was operated at a speed of travel of the head of .022 inches per minute for all loadings. The hydraulic machine was operated at as near this speed by hand as judgment would permit.

As already indicated the strain values were determined by means of the hydrostatic instrument, which was designed, constructed, and developed in the Materials Testing Laboratory. A complete description of this instrument is given in Bulletin No. 25 of the Engineering Experiment Station of the State College of Washington but will be described briefly here.

DESCRIPTION OF THE INSTRUMENT

The instrument works on the hydro-static principle that a definite quantity of liquid tends to maintain its volume constant.

Referring to Figure 1, the complete apparatus is divided into two main parts: that which clamps on the concrete cylinder, and the gage board.

The clamping or actuating part of the instrument is made up of two steel rings slightly larger than the concrete cylinder to which it is clamped (6″ x 12″ cylinders used) with three equally spaced clamping screws in each ring. Between the clamping rings are three equally spaced metallic bellows, attached at their upper ends directly to ears on the upper clamping ring. The bottom ends are attached through spacing rods and swivel joints to the lower clamping ring.

The upper end caps are designed to receive interconnecting pipes between the three bellows, while the central bellows has a connection for a flexible tube to lead to the gage board. The gage board is so arranged with valves and reservoirs that the instrument can be handled readily and the liquid level finally adjusted to zero in a small bore tube with an adjacent scale. As the concrete cylinder is loaded and therefore compressed the liquid level on the gage board will rise according to the displacement in the bellows.

The advantages of this type of instrument are: First, it compensates accurately for any bending action of the specimen tested, such as might occur with uneven surface pressure during loading. This is not true in all cases where mechanical types of measuring instruments are used. Second, it can be readily changed to different magnifying powers by substituting different diameter gage glasses to suit the particular needs of the test being conducted. Third, it is flexible, easily and quickly set up, requiring less than five minutes for the complete set up in routine testing. Fourth, there are no mechanical rubbing parts, and therefore no mechanical friction. The only friction would be the fluid friction and this becomes negligible for water as the working fluid. Fifth, referring to Table 2 it will bé noticed that the scale readings in metric units are appreciable even for unit stress values of 17.66 lb. per square inch on six inch cylinders. Thus the magnification for this instrument ranks with any type of instrument in use, whether optical or mechanical in type.

VERIFICATION OF RESULTS BY USING INSTRUMENTS OF OTHER TYPES

Certain verification and comparative data have been obtained since the material for this report was submitted to the printer. Please refer to Page 43 for full discussion of this data.

Table 1.

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
30	13	Lab.	.9	3¼	Concr. No. 1	2″-1″ Cr. Ba.†	1-2.25-2.79	2010	670		4.05‡		.95	2.84‡
30	14	"	.9	3¼	"	"	"	2280	760		3.63		.925	2.09
30	15	"	.9	3½	"	"	"	2870	956		3.85		.95	2.59
30	16	"	.9	3¼	"	"	"	2130	710		4.67		.965	3.48
30	17	"	9	3¼	"	"	"	2350	783		3.48		.89	.97
30	18	"	.9	3¼	"	"	"	2340	780		3.71		.90	1.90
30	Ave.	"	.9	3¼	"	"	"	2330	776		3.87		.93	2.31
8	24	"	.91	4	"	1″ ¼″ Cr Ba.	1-2-2.96	2390	796	730	3.65	3 72‡	.98	3.08
14	25	"	.91	4	"	"	"	2900	966	1010	4.42	4.42	1.0	4.42
28	27	"	.91	4	"	"	"	3110	1036	1200	4.35	4.35	1.0	4.35
65*	28	"	.91	4	"	"	"	3570	1190	1300	3.80	3.80	1.0	3.80
90*	29	"	.91	4	"	"	"	3560	1186	1100	3.92	3.92	1.0	3.92
121*	30	"	.91	4	"	"	"	3380	1123	1300	3.92	3.92	1.0	3.92
150*	31	"	.91	4	"	"	"	3720	1240	1500	4.00	4.00	1.0	4.00
180*	32	"	.91	4	"	"	"	3660	1220	1300	3.74	3.74	1.0	3.74
210*	33	"	.91	4	"	"	"	4270	1417	1800	4.08	4.08	1.0	4 08
256	34	"	.91	4	"	"	"	4000	1333	1835	4.34	4.34	1.0	4.34
56	35	"	.9	5	(⅔ Concr., ⅓ Plas)	1″-¼″ Cr Ba	"	4550	1517	1600	5.25	5.25	1.0	5.25
56	36	"	1.0	5	"	"	1-2 14-2 95	3530	1177	1600	4.16	4.16	1.0	4.16
56	37	"	1.0	5	"	"	"	3450	1150	1500	4.00	4.00	1.0	4.00
56	38	"	1.0	5	"	"	"	3160	1053	1450	3.70	3.70	1.0	3.70
56	39	"	1.0	5	"	"	"	3150	1050	1550	3.95	3.95	1 0	3.95
56	40	"	1.0	5	"	"	"	3460	1153	1450	3.95	3.95	1.0	3.95
195*	41	"	1.0	5	"	"	"	3680	1227	900	3.71	4.00	.982	3.40
195*	42	"	1.0	5	"	"	"	4280	1427	1200	4.20	4.34	.99	4.09
	Ave.	"	1.0	5	"	"	"	3530	1176	1380	3.95	4.01		3.90

* Tested dry.

† Cr. Ba. = Crushed Basalt.

‡ Multiply by 10^6.

Table 1. (Cont'd.)

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
29	43	''	.8	3½	Concr. No. 2	1″-¼″ Cr. Ba.	1-2.14-2.95	3720	1240	1200	4.75	4.75	1.0	4.75
29	44	''	.8	3½	''	''	''	3480	1160	900	4.90	5.0	.983	4.72
29	45	''	.8	3½	''	''	''	2970	990	1700	4.15	4.15	1.0	4.15
29	46	''	.8	3½	''	''	''	3150	1050	1200	4.25	4.25	1.0	4.25
29	47	''	.8	3½	''	''	''	3460	1150	1350	4.65	4.65	1.0	4.65
29	Ave.	''	.8	3½	''	''	''	3356	1118	1270	4.61	4.61	1.0	4.61
28	48	Lab	.8	3	Concr. No. 1	1″-¼″ Cr. Ba.	1-1.8-2.19	3730	1243	1500	3.77	3.77	1.0	3.77
28	49	''	.8	3	''	''	''	4646	1549	1550	4.30	4.30	1.0	4.30
28	50	''	.8	3	''	''	''	4050	1350	1400	4.24	4.24	1.0	4.24
28	51	''	.8	3	''	''	''	3940	1313	1500	4.24	4.24	1.0	4.24
28	52	''	.8	3	''	''	''	3820	1273	1100	3.43	4.45	.988	4.02
28	Ave.	''	.8	3	''	''	''	4090	1363	1410	3.99	4.20	.999	4.11
28	53	Lab.	.685	3¾	Concr. No. 1	1″-¼″ Cr. Ba.	1-1.51-1.91	3940	1313	1500	4.35	4.35	1.0	4.35
28	54	''	.685	3¾	''	''	''	3790	1263	1500	4.35	4.35	1.0	4.35
28	55	''	.685	3¾	''	''	''	3920	1307	1700	4.00	4.00	1.0	4.00
28	56	''	.685	3¾	''	''	''	3750	1250	1700	4.35	4.35	1.0	4.35
28	57	''	.685	3¾	''	''	''	3760	1253	1700	4.35	4.35	1.0	4.35
28	Ave.	''	.685	3¾	''	''	''	3820	1273	1620	4.28	4.28	1.0	4.28
28	58	''	.535	2½	Concr. No 1	1″-¼″ Cr. Ba.	1-1.03-1.32	4470	1490	1600	4.76	4.76	1.0	4.76
28	59	''	.535	2½	''	''	''	4830	1610	1600	4.76	4.76	1.0	4.76
28	60	''	.535	2½	''	''	''	4010	1337	1700	4.50	4.50	1.0	4.50
28	61	''	.535	2½	''	''	''	4780	1593	1700	4.72	4.72	1.0	4.72
28	Ave.	''	.535	2½	''	''	''	4522	1507	1650	4.71	4.71	1.0	4.71
32	62	Lab.	.8	1¾	Concr No. 3	1″-¼″ Cr. Ba.	1-2.14-2.70	3730	1240	1700	3.70	3.70	1.0	3.70
31	63	''	.8	1¾	''	''	''	3710	1233	1800	4.26	4.26	1.0	4.26
38	64	''	.8	1¾	''	''	''	4410	1470	1600	4.29	4.29	1.0	4.29
29	65	''	.8	1¾	''	''	''	3520	1173	1550	4.65	4.65	1.0	4.65
29	66	''	.8	1¾	''	''	''	3110	1037	1300	4.64	4.64	1.0	4.64
	Ave.	''	.8	1¾	''	''	''	3696	1232	1590	4.31	4.31	1.0	4.31

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
35	67	Lab.	.8	2¾	Ottawa Std.	1″-¼″ Cr. Ba.	1-1.79-3.12	2730	910	1200	5.12	5.12	1.0	5.12
35	68	"	.8	2¾	"	"	"	2960	987	1100	4.95	4.95	1.0	4.95
35	69	"	.8	2¾	"	"	"	3340	1113	1500	4.87	4.87	1.0	4.87
35	Ave.	"	.8	2¾	"	"	"	3010	1003	1267	4.98	4.98	1.0	4.98
	70	Field	.67	4		2½″-¼″ Gr.	1-2-3	3890	1297	1580	4.02	4.02	1.0	4.02
	71	"	.67	4		"	"	3780	1260	1250	4.07	4.07	1.0	4.07
	72	"	.67	4		"	"	4430	1477	1500	4.00	4.00	1.0	4.00
285*	73	"	.67	4		"	"	3300	1100	1200	3.70	3.70	1.0	3.70
255*	74	"	.67	1½		"	1-2.04-3.07	4780	1593	1400	4.24	4.32	.996	4.20
233*	75	"	.67	1½		"	"	5400	1800	1400	3.75	4.00	.967	2.96
256*	76	"	.67	1½		"	"	3800	1267	1350	4.29	4.29	1.0	4.29
260*	77	"	.67	1½		"	"	4840	1613	1820	4.25	4.25	1.0	4.25
229*	78	"	.67	1¾		"	1-2.04-2.80	4500	1500	1500	3.72	3.72	1.0	3.72
234*	79	"	.67	1¾		"	"	4420	1477	1600	3.84	3.84	1.0	3.84
247*	80	"	.67	1¾		"	"	5280	1760	1350	3.71	4.78	.97	3.68
248*	81	"	.67	1¾		"	"	4015	1338	1350	3.50	3.50	1.0	3.50
209*	82	"	.67	1¾		"	"	3810	1270	1340	3.68	3.68	1.0	3.68
215*	83	"	.67	1¾		"	"	4700	1567	1150	3.85	4.05	.97	3.04
246*	84	"	.67	1¾		"	"	3800	1267	1250	3.10	3.10	1.0	3.10
226*	85	"	.67	1¾		"	"	5480	1827	1300	3.80	4.00	.972	2.96
217*	86	"	.65	1¾		"	"	5200	1733	1725	4.00	4.00	1.0	4.00
206*	87	"	.65	1¾		"	"	5300	1767	1400	4.06	4.18	.985	3.63
205*	88	"	.65	1¾		"	"	4150	1383	1400	3.92	3.92	1.0	3.92
30	89	Stud.	1.09	1″	Concr. No. 1	1″-¼″ Cr. Ba.	1-2.62-3.42	2310	770	800	3.63	3.63	1.0	3.63
30	90	"	1.09	1	"	"	"	2710	903	920	2.88	2.88	1.0	2.88
30	91	"	1.09	1	"	"	"	2460	820	920	3.51	3.51	1.0	3.51
28	92	"	1.09	1	"	"	"	2180	727	780	3.65	3.65	1.0	3.65
28	93	"	1.09	1	"	"	"	2160	720	720	3.55	3.55	1.0	3.55
29	Ave.	"	1.09	1	"	"	"	2364	788	817	3.44	3.44	1.0	3.44
28	94	Stud.	.964	3	Concr No 1	1″-¼″ Cr. Ba.	1-2.13-2.69	3790	1260	1342	3.50	3.50	1.0	3.50

* Tested dry.

Table 1. (Cont'd.)

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
28	95	"	.964	3	"	"	"	3660	1220	1130	3.53	3.53	1.0	3.53
28	96	"	.964	3	"	"	"	3210	1070	1550	3.14	3.14	1.0	3.14
28	97	"	.964	3	"	"	"	4000	1333	1100	3.75	3.81	.998	3.80
28	98	"	.964	3	"	"	"	3190	1063	1100	3.80	3.80	1.0	3.80
28	Ave.	"	.964	3	"	"	"	3570	1190	1244	3.54	3.55		3.55
28	99	Stud.	.964	2	Concr. No. 1	1"-¼" Cr. Ba	1-2.13-2.69	2870	957	1025	3.33	3.33	1.0	3.33
28	100	"	.964	2	"	"	"	2780	927	1200	3.43	3.43	1.0	3.43
28	101	"	.964	2	"	"	"	3310	1103	1200	3.27	3.27	1.0	3.27
28	102	"	.964	2	"	"	"	2870	957	930	3.37	3.37	1.0	3.37
28	Ave.	"	.964	2	"	"	"	2962	987	1089	3.35	3.35	1.0	3.35
28	103	Stud.	.864	2	Concr. No. 1	1"-¼" Cr. Ba.	1-1 92-2.64	3320	1107	1400	3.63	3.63	1.0	3.63
28	104	"	.864	2	"	"	"	3710	1237	1340	3.42	3.42	1.0	3.42
28	105	"	.864	2	"	"	"	3840	1280	1340	3.45	3.45	1.0	3.45
28	106	"	.864	2	"	"	"	2970	.990	1300	3.54	3.54	1.0	3.54
28	107	"	.864	2	"	"	"	3460	1153	1300	3.65	3.65	1.0	3.65
28	Ave.	"	.864	2	"	"	"	3460	1153	1336	3.54	3.54	1.0	3.54
28	108	Stud.	.864	2	Concr. No. 1	1"-¼" Cr. Ba.	1-1 92-2.64	3830	1277	1340	3.63	3.63	1.0	3.63
28	109	"	.864	2	"	"	"	4180	1393	1340	3.78	3.78	1.0	3.78
28	110	"	.864	2	"	"	"	4260	1420	1411	3.79	3.79	1.0	3.79
28	111	"	.864	2	"	"	"	3990	1330	1200	3.64	3.68	.997	3.56
28	Ave.	"	.864	2	"	"	"	4065	1355	1323	3.71	3.72		3.69
28	112	Stud.	.96	2	Concr. No. 2	1"-¼" Cr. Ba.	1-2.43-3.03	3120	1040	1050	3.79	3.79	1.0	3.79
28	113	"	.96	2	"	"	"	3440	1147	1210	4.13	4.13	1.0	4.13
28	Ave.	"	.96	2	"	"	"	3280	1093	1130	3.94	3.94	1.0	3.94
28	114	Stud.	.96	2	Concr. No. 3	1½-¼" Grav	1-2.51-4.45	3060	1020	1200	3.68	3.68	1.0	3.68
28	115	"	.96	2	"	"	"	2730	910	990	3.82	3.82	1.0	3.82
28	Ave.	"	.96	2	"	"	"	2895	965	965	3.75	3.75	1.0	3.75
28	116	Stud.	1.05	1	Concr. No. 1	1"-¼" Cr. Ba.	1-2.58-3.25	2220	740	780	3.78	3.78	1.0	3.78
28	117	"	1.05	1	"	"	"	1860	620	610	3.27	3.27	1.0	3.27

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult	Unit Stress ⅓ Ult	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
28	118	"	1.05	1	"	"	"	1700	567	700	3.50	3.50	1 0	3.50
28	119	"	1.05	1	"	"	"	2240	747	800	3.65	3.65	1.0	3.65
28	Ave.	"	1.05	1	"	"	"	2005	668	722	3.55	3.55	1 0	3.55
28	121	Stud	.96	1	Concr No. 1	1″-¼″ Cr. Ba.	1-2 12-2 68	2750	917	1000	4.16	4.16	1.0	4.16
28	122	"	.96	1	"	"	"	3060	1020	1200	3.45	3.45	1 0	3.45
28	123	"	.96	1	"	"	"	2660	887	870	4.45	4.45	1.0	4.45
28	124	"	.96	1	"	"	"	2650	883	630	4.05	4.20	.99	3.82
28	125	"	.96	1	"	"	"	2880	960	1000	4.36	4.36	1.0	4.36
28	Ave.	"	.96	1	"	"	"	2780	927	933	4.10	4.12		4.19
28	126	Stud.	.859	1¼	Concr. No. 1	1″-¼″ Cr. Ba	1-1.92-2 45	3120	1040	1270	4.13	4.13	1.0	4.13
28	127	"	859	1¼	"	"	"	2860	953	1200	3.77	3.77	1.0	3.77
28	128	"	.859	1¼	"	"	"	2870	957	800	4.33	4.37	.996	4.30
28	129	"	859	1¼	"	"	"	3240	1080	1060	4.16	4.16	1.0	4.16
28	130	"	.859	1¼	"	"	"	2896	965	1260	4.30	4.30	1.0	4.30
28	131	"	.856	1¼	"	"	"	2800	933	1050	4.46	4.46	1.0	4.46
28	Ave.	"	.859	1¼	"	"	"	2963	988	1106	4.19	4.20		4.18
49	132	Lab.	1 0	4½	§Sand No. 4	2″-¼″ Cr. Ba.	1-2.65-3 16	3040	1013	1300	3.70	3.70	1.0	3.70
45	133	"	1.0	4½	"	"	"	3070	1023	1100	4.24	4.24	1.0	4.24
45	134	"	1.0	4½	"	"	"	2690	897	1200	4.26	4.26	1.0	4.26
45	135	"	1.0	4½	"	"	"	3000	1000	1150	3.80	3.80	1.0	3.80
46	Ave	"	1.0	4½	"	"	"	2950	983	1190	4.00	4.00	1.0	4.00
7	136	Lab.	.9	6½	Sand No 4	1½-¼″ Cr. Ba.	1-2 0-3.8	1530	510	600	3.07	3.07	1.0	3.07
39	137	"	.9	6½	"	"	"	3670	1223	1300	4.34	4.34	1 0	4.34
44	139	"	.9	6½	"	"	"	3470	1157	1410	4.00	4.00	1.0	4.00
44	140	"	.9	6½	"	"	"	3100	1033	1130	4.16	4.16	1.0	4.16
41	Ave.	"	.9	6½	"	"	"	3410	1137	1280	4.17	4.17	1.0	4.17
7	141	Lab.	.964	4½	Sand No 4	1½″-¼″ Grav.	1-2 35-3.7	1620	540	635	3.02	3.02	1.0	3.02
36	142	"	.964	4½	"	"	"	3450	1150	1100	4.14	4.14	1.0	4.14
43	143	"	.964	4½	"	"	"	3640	1314	1350	3.86	3.86	1.0	3.86
44	144	"	.964	4½	"	"	"	3260	1087	1400	4.16	4.16	1.0	4.16

§ Sand No. 4 is a mixture of ⅔ Concrete No. 4 and ⅓ Plaster No 4

Table 1. (Cont'd.)

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
45	145	"	.964	4½	"	"	"	2900	967	1000	4.10	4.10	1.0	4.10
42	Ave.	"	.964	4½	"	"	"	3316	1105	1212	4.06	4.06	1.0	4.06
7	146	Field		3	Sand No. 4	2″-¼″ Cr. Ba.	1-2.6-3.2	1318	439	460	3.33	3.33	1.0	3.33
7	147	"		7	"	"	"	1206	402	450	2.67	2.67	1.0	2.67
7	148	"		5	"	"	"	1212	404	450	2.95	2.95	1.0	2.95
7	149	"		3¼	"	"	"	1650	550	550	3.05	3.05	1.0	3.05
7	150	"		5½	"	"	"	1560	520	575	3.12	3.12	1.0	3.12
7	151	"		5¼	"	"	"	1276	428	450	3.00	3.00	1.0	3.00
7	152	"		2¾	"	"	"	1518	506	400	3.11	3.28	.991	3.00
7	153	"		3	"	"	"	1299	433	425	2.67	2.67	1.0	2.67
7	154	"		7	"	"	"	1375	458	490	3.13	3.13	1.0	3.13
7	155	"		6	"	"	"	1328	433	440	3.14	3.14	1.0	3.14
7	Ave.	"		4.8	"	"	"	1377	459	469	3.02	3.04		3.01
37	156	Field		7	Sand No 4	2″-¼″ Cr. Ba.	1-2.6-3.2	2860	953	800	3.58	3.70	.995	3.56
36	157	"		5	"	"	"	3070	1023	1300	3.92	3.92	1.0	3.92
35	158	"		3¼	"	"	"	3430	1143	920	4.30	4.50	.99	4.10
37	159	"		5½	"	"	"	2950	983	1000	4.73	4.73	1.0	4.73
35	160	"		5¼	"	"	"	2860	953	1300	4.35	4.35	1.0	4.35
35	161	"		2¾	"	"	"	3060	1020	1050	4.07	4.07	1.0	4.07
34	162	"		3	"	"	"	2640	880	1000	3.87	3.87	1.0	3.87
32	163	"		7	"	"	"	2480	827	930	4.14	4.14	1.0	4.14
37	164	"		5¼	"	"	"	2700	900	1000	4.00	4.00	1.0	4.00
30	165	"		5¼	"	"	"	2850	950	950	4.18	4.18	1.0	4.18
29	166	"		2½	"	"	"	2905	968	1000	4.35	4.35	1.0	4.35
28	167	"		6	"	"	"	3080	1027	1027	4.16	4.16	1.0	4.16
28	168	"		4½	"	"	"	3115	1038	1350	4.34	4.34	1.0	4.34
28	169	"		5½	"	"	"	2490	830	1300	3.97	3.97	1.0	3.97
28	170	"		5	"	"	"	2250	750	900	3.89	3.89	1.0	3.89
44	171	"		2½	"	"	"	2710	903	1150	4.22	4.22	1.0	4.22

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
43	172	"		6	"	"	"	4460	1487	1987	4.17	4.17	1.0	4.17
42	173	"		4½	"	"	"	3590	1197	1250	3.90	3.90	1.0	3.90
39	174	"		5½	"	"	"	3340	1113	1400	3.82	3.82	1.0	3.82
37	175	"		5	"	"	"	2920	973	1200	4.17	4.17	1.0	4.17
38	176	"		2½	"	"	"	2710	903	1150	4.22	4.22	1.0	4.22
35	Ave.	"			"	"	"	2920	973	1135	4.11	4.13		4.10
7	177	Field		5¼	Sand No 4	1½"-¼" Grav	1 2.5-4.4	1600	533	500	2.96	3.34	.998	2.96
7	178	"		7¼	"	"	"	1220	407	400	2.82	2.82	1.0	2.82
7	179	Field		6½	Sand No 4	1½"-¼" Grav.	1-2.7-4.4	917	306	400	2.19	2.19	1.0	2.19
7	180	"		6	"	"	"	1094	365	500	2.12	2.12	1.0	2.12
7	181	"		5½	"	"	"	1015	338	400	2.52	2.52	1.0	2.52
7	Ave.	"		6	"	"	"	1009	336	433	2.28	2 28	1.0	2.28
30	182	Field		5¼	Sand No 4	1½"-¼" Grav.	1-2.5-4.4	2520	840	988	4.03	4.03	1.0	4.03
30	183	"		5¼	"	"	"	2830	943	950	3.70	3.70	1.0	3.70
30	184	"		5¼	"	"	"	2790	930	800	4.00	4.10	.995	3.84
29	185	"		7¼	"	"	"	2170	723	800	3.56	3.56	1.0	3.56
28	186	"		6	"	"	"	2630	877	860	4.00	4.00	1.0	4.00
28	187	"		6	"	"	"	2470	823	850	4.04	4.04	1.0	4.04
28	188	"		6½	"	"	"	2690	897	1100	3.65	3.65	1.0	3.65
28	189	"		6½	"	"	"	2500	833	900	3 52	3.52	1.0	3.52
29	190	"			"	"	"	2990	997	1100	3 77	3.77	1 0	3.77
29	191	"			"	"	"	2530	843	910	3.60	3.60	1.0	3.60
28	192	Field		5¼	Sand No 4	1½"-¼" Grav.	1-2 5-4.4	2660	886	900	3.90	3.90	1.0	3.90
29	193	"		5¼	"	"	"	2910	970	1050	3.89	3.89	1.0	3.89
28	194	"		7	"	"	"	2830	943	950	3.90	3.90	1.0	3.90
28	195	"		7	"	"	"	2580	860	920	3.65	3.65	1.0	3.65
28	196	"		6	"	"	"	2990	967	1200	4.06	4.06	1 0	4.06
28	197	"		6	"	"	"	3170	1057	1100	3.75	3.75	1.0	3.75
29	Ave	"		6	"	"	"	2760	920	960	3.81	3.81	1.0	3.81
28	198	Field		6	Sand No 4	1½"-¼" Grav.	1-2.7-4.4	2120	707	910	3.89	3 89	1.0	3.89

Table 1. (Cont'd.)

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress ⅓ Ult.	Unit Stress El. Lim	E at ⅓ Ult.	E at El. Lim.	n at ⅓ Ult.	K at ⅓ Ult.
28	199	״		6¼	״	״	״	2000	667	670	4.00	4.00	1.0	4.00
28	200	״		5½	״	״	״	2120	707	1000	4.00	4.00	1.0	4.00
28	201	״		5½	״	״	״	2118	706	710	3.90	3.90	1.0	3.90
28	202	״		5½	״	״	״	2260	753	760	3.90	3.90	1.0	3.90
28	203	״		5½	״	״	״	2030	677		3.64		.971	2.92
28	204	״		5½	״	״	״	1820	607		3.64		.971	2.92
28	205	״		5¼	״	״	״	2270	757	850	3.65	3.65	1.0	3.65
28	206	״		5¼	״	״	״	2370	790	820	3.47	3.47	1.0	3.47
28	207	״		6	״	״	״	2810	937	936	3.80	3.80	1.0	3.80
28	208	״		6	״	״	״	2910	970	970	3.89	3.89	1.0	3.89
28	209	״		6	״	״	״	2650	883	1130	3.35	3.35	1.0	3.35
28	210	״		6	״	״	״	2220	740	750	3.27	3.27	1.0	3.27
28	211	״		6	״	״	״	2400	800	850	3.72	3.72	1.0	3.72
28	212	״		6	״	״	״	2610	870	900	3.73	3.73	1.0	3.73
28	213	״		6	״	״	״	2170	723	800	3.87	3.87	1.0	3.87
28	214	״		6	״	״	״	2110	703	750	3.62	3.62	1.0	3.62
28	215	״		5½	״	״	״	2830	943	1200	3.56	3.56	1.0	3.56
28	216	״		6½	״	״	״	2540	847	850	3.61	3.61	1.0	3.61
28	217	״		6½	״	״	״	2540	847	920	3.14	3.14	1.0	3.14
28	Ave.	״			״	״	״	2340	780	875	3.68	3.69		3.61
531*	218	Field	.67	1½		2"-¼" Grav.		3220	1073	1340	3.92	3.92	1.0	3.92
529*	219	״	.67	1½		״		2590	863	1300	1.82	1.82	1.0	1.82
481 *	220	״	.67	1½		״	1-2.04-3.07	3670	1223	1400	3.68	3.68	1.0	3.68
473*	221	״	.67	1½		״	״	2800	933	1150	3.02	3.02	1.0	3.02
469*	222	״	.67	1¾		״	1-2.04-2.8	2830	943	1200	3.22	3.22	1.0	3.22
479*	223	״	.67	1¾		״	״	3450	1150	1100	3.03	3.03	1.0	3.03
471*	224	״	.67	1¾		״	״	2560	853	1200	3.10	3.10	1.0	3.10
475*	225	״	.67	1¾		״	״	5120	1707	2000	4.35	4.35	1.0	4.35

* Tested dry.

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress 1/3 Ult	Unit Stress El. Lim	E at 1/3 Ult.	E at El. Lim.	n at 1/3 Ult.	K at 1/3 Ult.
470*	226	"	.67	1¾		"	"	3155	1052	1400	3.35	3.35	1.0	3.35
455*	227	Field	.67	1½		2"-¼" Grav.	1-2.04-3.07	4290	1430	1550	3.10	3.10	1.0	3.10
461*	228	"	.67	1½		"	"	3640	1213	1200	3.12	3.12	1.0	3.12
462*	229	"	.67	1¾		"	1-2 04-2.8	3800	1267	1270	2.82	2 82	1 0	2.82
463*	230	"	.67	1¾		"	"	3170	1057	1100	3.07	3.07	1.0	3.07
458*	231	"	.67	1¾		"	"	4330	1443	1650	3.65	3.65	1.0	3.65
443*	232	"	67	1¾		"	"	3185	1062	1230	3.15	3.15	1.0	3.15
	Ave.	"	.67			"		3410	1137	1286	3.19	3.19	1.0	3.19
115*	233	Field				2"-¼" Grav.		4220	1407	1700	4.04	4.04	1.0	4.04
120*	234	"				"		1450	1483	2000	5.37	5.37	1.0	5.37
97*	235	"				"		5180	1727	2000	4.65	4.65	1.0	4.65
100*	236	"				"		3830	1277	1500	4.35	4.35	1.0	4.35
109*	237	'				"		4360	1453	1550	4.03	4.03	1.0	4.03
94*	238	'				"		3800	1267	1650	4.50	4.50	1.0	4.50
	Ave.	"				"		4270	1423	1678	4.32	4.32	1.0	4.32
7	239	Lab.	1 11	2	Concr No. 1	1½"-¼" Grav.	1-2 5-4.64	1530	510	600	2.78	2.78	1 0	2.78
28	240	"	1.11	2	"	"	"	2540	847	950	3.90	3.90	1.0	3.90
28	241	"	1.11	2	"	"	"	2320	773	900	3.71	3.71	1.0	3.71
28	Ave.	"	1.11	2	"	"	"	2430	810	925	3.80	3.80	1.0	3 80
9	242	Lab.	1.17	1	Fuller's Curve for Grading			1870	623	710	3.10	3.10	1.0	3.10
28	243	"	1.17	1	"	" " "		2333	778	885	3.91	3.91	1.0	3.91
28	244	"	1.17	1	"	" " "		2462	821	955	3.80	3.80	1.0	3.80
	Ave.	"	1 17	1	"	" " "		2397	799	920	3.85	3.85	1.0	3.85
28	245	Stud.	1.1	4	Concr No. 1	1½"-¼" Grav.	1-2 48-3 70	2590	863	1100	3.30	3.30	1.0	3 30
28	246	"	1.1	4	"	"	"	2600	867	1050	3.22	3.22	1.0	3.22
28	247	"	1.1	4	"	"	"	2560	853	1060	2.97	2.97	1.0	2.97
28	248	"	1.1	4	"	"	"	2730	910	1050	3.20	3.20	1.0	3.20
28	Ave.	"	1.1	4	"	"	"	2622	874	1065	3 17	3.17	1.0	3.17
28	249	Lab.	1.1	6	Fuller's Curve for Grading			2333	778	880	4.00	4.00	1.0	4.00

* Tested dry.

Table 1. (Cont'd.)

Age Days	File	Mixed	Water Cement Ratio	Slump	Fine Aggregate	Coarse Aggregate	Mix dry-rodded	Unit Stress Ult.	Unit Stress 1/3 Ult.	Unit Stress El. Lim	E at 1/3 Ult.	El. Lim.	n at 1/3 Ult.	K at 1/3 Ult.
28	250	"	1.1	6	"	" " "		2050	683	780	4.00	4.00	1.0	4.00
28	Ave.	"	1.1	6	"	" " "		2190	730	830	4.00	4.00	1.0	4.00
28	251	Stud.	1.15	1	Concr No. 1	1½"-¼" Grav	1 2.59-4.44	2050	683	700	3.33	3.33	1.0	3.33
28	252	"	1.15	1	"	"	"	2190	730	812	3.11	3.11	1.0	3.11
28	253	"	1.15	1	"	"	"	2130	710	812	3.04	3.04	1.0	3.04
28	254	"	1.15	1	"	"	"	2195	732	778	3.36	3.36	1.0	3.36
28	Ave.	"	1.15	1	"	"	"	2141	714	775	3.28	3.28	1.0	3.28
28	255	Stud.	1.1	4	Concr. No 1	1½"-¼" Grav	1-2.3-3.47	2760	920	1150	3.15	3.15	1.0	3.15
28	256	"	1.1	4	"	"	"	2560	853	1050	3.17	3.17	1.0	3.17
28	257	"	1.1	4	"	"	"	3040	1013	1200	3.22	3.22	1.0	3.22
28	258	"	1.1	4	"	"	"	2950	983	1060	3.19	3.19	1.0	3.19
28	259	"	1.1	4	"	"	"	2790	930	1050	3.37	3.37	1.0	3.37
28	Ave.	"	1.1	4	"	"	"	2820	940	1102	3.22	3.22	1.0	3.22
72*	260	Field						5720	1907	1800	4.43	4.46	.996	4.40
61*	261	"						2260	753	813	3.43	3.43	1.0	3.43
64*	262	"						3270	1090	1130	3.97	3.97	1.0	3.97
60*	263	"						2810	937	1270	3.09	3.09	1.0	3.09
56*	264	"						2410	803	1025	3.21	3.21	1.0	3.21
69*	265	"						4480	1493	1500	4.02	4.02	1.0	4.02

* Tested dry.

DATA

Table 1 represents the vital data obtained from two hundred and forty six 6" x 12" concrete cylinders tested during the past year. In this table will be found the age of the cylinder in days when tested, whether damp or dry at test, whether made in the laboratory or in the field, the water cement ratio if available, the approximate grading of both the fine and coarse aggregate, the type of coarse aggregate whether crushed basalt or gravel, the slump of the mix when poured, and the dry-rodded mix or in some cases the field mix. The values obtained in testing the cylinders include the ultimate strength, one-third ultimate strength, the proportional limit, all in pounds per square inch, and also the modulus of elasticity at one-third ultimate strength, the modulus of elasticity at the proportional limit, and the values of n and k for the equation $S = k\ d^n$ ① taken at one-third ultimate strength.

Table 2 is a copy of the readings made in testing cylinders Nos. 225 and 239. Figure 2, Curve Nos. 1 and 2 give the readings for cylinders Nos. 225 and 239 plotted on rectangular coordinates. Curves Nos. 1 and 2, Figure 3, are the same data plotted on logarithmic cross section paper. The logarithmic plotting magnifies the errors in the early part of the curve It is the purpose of Table 2 and Figures 2 and 3 to illustrate the data obtained in testing each cylinder listed in Table 1. It also illustrates the scale readings in centimeters that are obtained with increments of load as low as 17.6 pounds per square inch. The above cylinders were selected because they represent approximately the extremes in ultimate strength.

When examining curves Nos. 1 and 2, Figure 2, it will be noticed that they do not intersect the origin. Both of these tests were made on the screw type testing machine. When testing cylinders on the hydraulic type testing machine the starting error was even greater. It has been customary to correct for this error by drawing a line parallel with the plotted points but passing through the origin. Some may question this procedure, thinking that this initial curvature is due to the action within the concrete.

① This is the equation used by Mr. Stanton Walker in Bulletin No. 5 published by The Structural Materials Research Laboratory, April, 1923. (See page 26 of this bulletin for explanation.)

Table 2.

Compression test for concrete cylinders

Load Lbs.	Stress Lbs. per. sq. in.	Cylinder No. 225 Reading on Gauge Board in cm.	Cylinder No. 225 Deformation inches per inch of length	Cylinder No. 239 Reading on Gauge Board in cm.	Cylinder No. 239 Deformation Inches per inch of length
500	17.7		‡	0.4	7.0 ‡
1000	35.3	0.4	7.0	0.8	14.0
1500	53.0			1.1	19.2
2000	70.6	0.9	15.75	1.4	24.5
2500	88.5			1.8	31.5
3000	106.0	1.3	22.7	2.1	36.8
3500	125.4			2.4	42.0
4000	141.2	1.8	31.5	2.7	47.2
4500	159.0			3.1	54.3
5000	176.5	2.25	39.4	3.4	59.5
5500	194.5			3.7	64.7
6000	212.0	2.75	48.1	4.1	71.5
6500	230.0			4.5	78.7
7000	247.0	3.2	56.0	4.9	85.8
7500	265.0			5.2	91.0
8000	282.0	3.7	64.7	5.6	98.0
8500	300.8			6.0	105.0
9000	318	4.2	73.5	6.3	110.0
9500	336			6.6	115.5
10000	353	4.65	81.4	7.0	122.5
11000	388	5.05	88.4	7.7	134.5
13000	459	6.0	105.0	9.1	159
14000	494	6.5	113.8	9.9	173
15000	529	7.0	122.5	10.6	185
16000	565	7.4	129.5	11.4	199
17000	600	7.9	138.4	12.2	213
18000	635	8.3	145.0	13.0	227
19000	670	8.8	154.0	13.8	241
20000	706	9.4	164.5	14.6	255
21000	742	9.8	171.5	15.4	269
22000	778	10.3	180.0	16.2	283

‡ Multiply 10^{-6}

Table 2 (Cont'd)

Compression test for concrete cylinders

		Cylinder No. 225		Cylinder No. 239	
Load Lbs.	Stress Lbs per. sq in.	Reading on Gauge Board in cm.	Deformation Inches per inch of length	Reading on Gauge Board in cm.	Deformation Inches per inch of length
23000	812	10.75	188.0	17 0	297
24000	849	11.25	197.0	17.9	313
25000	885	11.75	205.5	18.8	329
26000	918	12.2	214	19 6	343
27000	954	12 6	220	20.7	362
28000	988	13.1	229	21.7	380
29000	1025	13 6	238	22.6	395
30000	1059	14.05	246	23.7	415
31000	1096 5			24 9	436
32000	1130	14 9	261	26.1	457
33000	1167			27.3	478
34000	1200	15.9	278	28.7	502
35000	1254			30 0	525
36000	1273	16.9	296	31.5	550
37000	1309			32.9	576
38000	1341	17 8	312	34.6	605
39000	1379			36.2	634
40000	1411	18 7	328	38 0	665
42000	1485			42.0	735
44000	1556	20.7	362	47.8	836.5
46460	1643 3				
48000	1695	22.6	396		
52000	1835	24.6	430		
56000	1987	26 5	464		
60000	2120	28.6	500		
64000	2260	30.6	536		
68000	2400	32.6	570		
72000	2540	34.6	605		
76000	2680	36.7	642		
80000	2820	38.8	679		

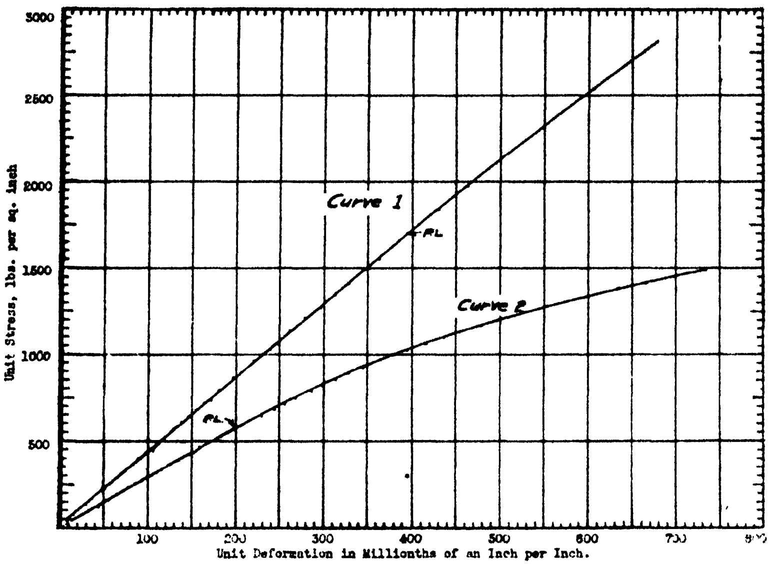

Figure 2.

Figure 4 is exhibited at this time to show that the initial curvature is due to other conditions rather than representing true deformations within the concrete. One cylinder was tested consecutively five times under as many different circumstances up to a stress estimated to be one-third of its ultimate strength.

Curve No. 1, Figure 4 is a plot of the results obtained when the cylinder was tested in the screw machine. The cylinder and instrument were then transferred to the hydraulic machine and tested under the same conditions. Curve No. 2 is the result of this test. The instrument was now completely removed and both cylinder and instrument were loaded into an automobile and transported to the Highway Laboratory at the University of Idaho. Here it was reassembled for testing in a 200,000 pound screw type machine with a single spherical head. The conditions for loading were different in that the machine was set in motion at low speed and the readings were read without stopping the machine to balance at each load increment as was done in the case of all of the rest of the tests.

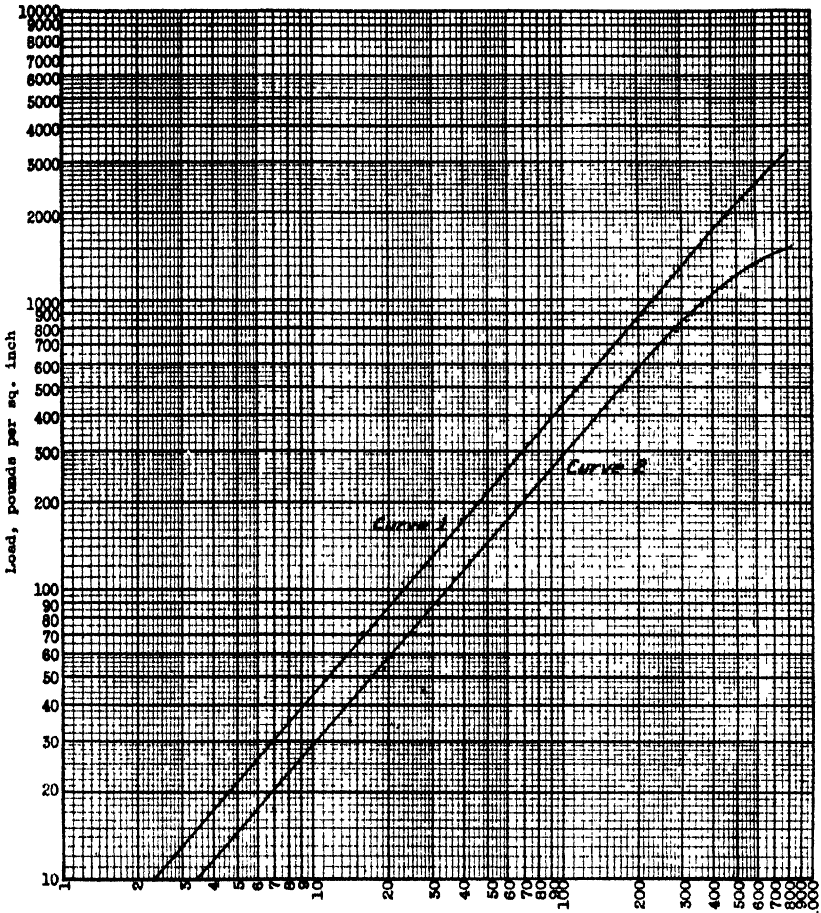

Figure 3.

Curve No. 4, Figure 4 is the resulting plot. Again the cylinder and instrument were transferred to a 50,000 pound screw machine with one spherical head without detaching the instrument. Curve No. 3, Figure 4 is the result. The equipment was again dismantled and removed to the State College of Washington Laboratory. With an interval of one week the cylinder was again tested in the 200,000 pound screw machine as for Curve No. 1, Figure 4, and Curve No. 5 is the result.

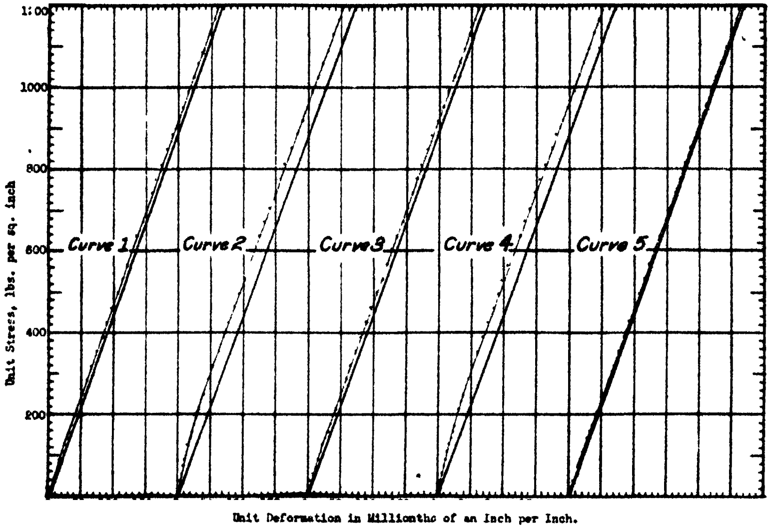

Figure 4.

As a result of the above series of tests several observations can be made.

First. From the fact that Curve No. 4 was a result of testing without balancing at each increment. it would seem that the method of loading is not vital within limits.

Second. When all of the curves of Figure 4 are corrected to zero by drawing a line through the origin and parallel with the straight section of the curve the total unit deformation at 1200 pounds per square inch stress has a variation not greater than .000002 inches from the mean of the five tests or about .7 of 1%.

The maximum variation of the plotted lines from the mean of the corrected curves at 1200 pounds per square inch stress is the same for Curves Nos. 2 and 4 or .000012 inch. Inasmuch as the plotted curves vary at this same stress by .000010 inch, it is reasonable to conclude that the testing machines are responsible for most of the curvature in the lower stress values.

In other words, the curvature found in the lower stress regions is due to a lack of accuracy in the weighing of loads

on the testing machine, or in part due to the compressometer, the temperature changes affecting the concrete, or the testing machine or instrument, and is not indicative of the true deformation within the concrete.

In the case of curves Nos. 1, 3, and 5, a straight line can be drawn through the points from a unit stress of 130 pounds per square inch to 1200 pounds per square inch. Surely the same condition of elasticity exists from zero load to 130 pounds per square inch stress.

It has been customary whenever necessary to correct the curves drawn for each cylinder to zero as shown in Figure 4. Whenever possible the testing machine giving the least error has been used. In many cases no correction has been found necessary. The compressometer was always adjusted to zero before applying load to the cylinder.

Third. It is interesting to note that the testing machine used for Curves Nos. 1 and 3 were of the same make and type but varied in size. The testing machines used for Curves Nos. 2 and 4 were made by a different manufacturer than that used for Curves Nos. 1 and 3. These machines were of the same capacity but varied as to type.

OBSERVATIONS AND DISCUSSION OF RESULTS

Concrete can be considered elastic in the same sense that the other engineering materials have been considered elastic for many years past.

Concrete is made by thousands of people under as many conditions. Its quality and durability vary widely. To say that the above statement holds for all concrete would be absurd. It is true, however, for well designed concrete, made from suitable materials properly graded. It is true for the bulk of concrete made at the present time which is made under proper specifications and control for highways, buildings, bridges, etc.

It is not out of order at this time to review some of the work that has been done to determine the modulus of elasticity of concrete.

In Vol. XIX, Part II, 1919, of the Proceedings of the American Society of Testing Materials, was published the outstanding work in regard to the Modulus of Elasticity of concrete. This work was done by Mr. Stanton Walker at the Structural Materials Research Laboratory, Lewis Institute, Chicago. In 1923 this work was reprinted with a few revisions as Bulletin No. 5, of the above laboratory, and entitled "Modulus of Elasticity of Concrete."

In this bulletin Mr. Walker gives the results of some 4000 tests of 6" x 12" concrete cylinders covering various proportions and types of aggregates.

There is very little doubt but that this work has been accepted by those interested in the "trade." To prove this point one need only refer to our text books on Materials of Construction published both in this country and abroad.

Mr. Walker used the Johnson Wire Wound instrument in the first part of the tests, but later substituted the Ames dial with five point contact. (For description of this instrument see Bulletin No. 5, described above, page 8.)

Mr. Walker introduces the equation previously referred to:

$S = k\ d^n$ as representing the relation between the stress and deformation, where S = unit stress in pounds per square inch

D = unit deformation in inches per inch

k = a constant

n = an exponent

If the stress-deformation relations are proportional up to a definite point then the exponent n becomes 1.0 and k is equal to E, the modulus of elasticity. Of course, these values of n and k only hold as long as the stress-strain relations are proportional. Beyond the proportional limit the value of n must be less than unity and the value of k must be less than the value of E. On logarithmic cross-section plotting the value of n is equal to the tangent of the slope of the curve. If the value of n is 1.0 then the slope of the curve is 45°.①

① For a complete discussion of this equation and the method of solving for n and k see pages 10 to 16, Bulletin No. 5, Structural Materials Research Laboratory, Lewis Institute.

In checking through the tables recording the data in Bulletin No. 5, in only one case representing five cylinders do we find the value of n equal to 1. In other words, Mr. Walker did not find concrete elastic in any portion of the stress-strain diagram, and in fact the average value of n is about .9 and the value of k was always less than the value of E for the cylinder tested.

A review of Table 1 will show 96 percent of the cylinders elastic in some portion of the stress-strain relationship while 88 percent are elastic up to or above one-third of the ultimate stress. The value of n for this data can be considered equal to 1.0 and the value of k can be considered equal to E for a stress equal to one-third of the ultimate stress.

Those cases where n is less than 1.0 and k less than E can as a rule be explained by some condition peculiar to the concrete or to the method of testing.

In the proceedings of the American Society for Testing Materials,① Mr. A. N. Johnson, Dean, College of Engineering, University of Maryland, exhibits material on "Direct Measurement of Poisson's Ratio for Concrete."

Dean Johnson used the Marten's Mirror Extensometer, (a description of which can be found in Marten's Handbook of Testing Materials,) and exhibits data covering the compression tests of nine concrete cylinders. In all cases he shows that the concrete is elastic and there is a definite proportional limit which occurs at 25% of the ultimate strength for the average of the cases given.

Again in "Public Roads"② Dean Johnson reports test of 112 cores drilled from highways in the State of Maryland. He states in part, "One marked characteristic that the mirror-extensometer readings give to the stress-strain curve for concrete in compression is the persistency of a straight line relationship in the earlier part of the curve for the lower pressures and the gradual departure from a straight line forming a very gradual curve for the higher pressures. The extent of the straight line relationship or proportionality may be

① Volume 24, 1924, Part 2, page 1024.
② Vol. 9, No. 8, (October, 1928.)

approximately determined and is taken to be the elastic limit of the concrete."

In "Engineering"① (London), Mr. V. C. Davies describes an Extensometer for the Determination of Young's Modulus for Concrete which operates on a combined mechanical and optical principle. A plate (Figure 6) showing six stress-strain relations in tension of concrete is included and the following comment is made.

"For the straight-line part of the graph, the value of E works out between 4,200,000 poundc and 4,400,000 pounds per square inch."

Although this article deals with the design of an extensometer for the purpose of reading extensions in concrete, the meager results reported are significant.

Mr. James W. Johnson in his bulletin "Relationship Between Strength and Elasticity of Concrete in Tension and Compression."② under "Summary and Conclusions,"③ states in part:

"For any load, above 25% of the ultimate, there is a small deformation not recovered upon the removal of the load. The amount of this unrecovered deformation depends on the amount of load, and the number of loadings, but becomes less for each succeeding load."

And again, "Although the stress-strain relationship for the first application of load is a curve, for both tension and compression, the stress-strain relationship for the second application of load up to the stress of the first loading, is a straight line for compression, and approaches closely a straight line for tension. For a repeated number of loadings up to or above 50% of the ultimate, in compression, the stress-strain curves even reverse in direction of curvature."

Additional references could be given, however, those given show the change in our conception of the elastic properties of concrete in the last six years. In 1923 Mr. Stanton Walker concluded that concrete was not elastic. In 1924 Dean A. N. Johnson gave a very limited

① Vol. CXXV, No. 3238, (February 3, 1928.)
② Bulletin No. 90, Engineering Experiment Station, Iowa State College of Agriculture and Engineering.
③ Pages 6 and 7.

amount of data that indicated concrete was elastic. Again in 1928 Dean A. N. Johnson exhibited considerable data both on road cores and molded cylinders that indicated elastic relationship. At the same time other investigators using practically the same type of apparatus have not found elastic relationship on the first loading, but upon consecutive loadings have found elastic relationship.

It is impossible at the present time to fully explain the difference in the results of the various investigators but some of the variable factors that would have to be studied in making such an explanation can be listed as follows:

1. Accuracy and sensitivity of the testing machine.
2. Accuracy and sensitivity of the measuring instrument.
3. The method of conducting the tests.
    a. Speed of loading.
    b. Load increment used.
    c. Condition of concrete, dry or damp
    d. Temperature changes.
4. The physical properties of the aggregates.
    a. Grading of both fine and coarse material.
    b. The base of the aggregate, whether granite, limestone, etc.
    c. Crushed rock or gravel coarse aggregate.
    d. Stress-strain relationship of the basic material of the aggregates.
5. Richness of the mix.
6. Age at test and method of curing.
7. Workability or slump when poured.
8. Care and accuracy in conducting all phases of the tests.

That the accuracy and sensitivity of the testing machine must be considered is shown by Figure 4. In fact this point has had a very decided effect upon the work conducted in the Materials Testing Laboratory.

Unquestionably item No. 2 is responsible for a number of erroneous conclusions in regard to the elastic properties of concrete as the above references indicate.

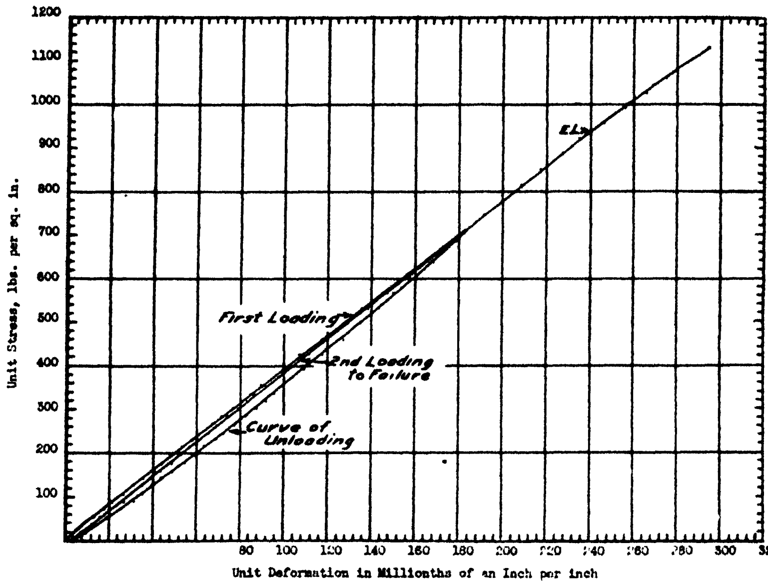

Figure 5.

Perhaps a considerable part of the question that exists at the present time in regard to the elastic properties of concrete could be eliminated if the variables listed above could be completely standardized or eliminated between the various experimenters.

Figure 5 shows the results obtained upon loading cylinder No. 240 up to twenty-eight percent of its ultimate strength, then decreasing the load in exactly the same manner used for its initial loading until the load was entirely removed. Without any readjustments the cylinder was reloaded to failure.

In the first loading there is a slight initial curvature up to an initial stress of 60 pounds per square inch. Beyond this point the stress-strain relationship is a straight line. The curve of unloading shows considerable "hysteresis effect" but approaches zero within 3 millionths of an inch per inch, indicating that the hysteresis is almost if not entirely in the testing machine.

The second curve of loading shows a straight line relationship and intersects the first loading at 706 pounds per square inch stress and shows an elastic limit at 920 pounds per square inch.

If the first curve of loading is corrected to zero the two curves of loading are out of parallel by not more than .000004 of an inch per inch, between zero and a stress of 706 pounds per square inch. The author believes that these curves should have been parallel.

The results observed from the tests of Figure 5 are:

I. That, providing the elastic limit is not exceeded, the first loading indicates a straight line relationship as well as the second loading.

2. That, providing the elastic limit is not exceeded, no permanent deformation takes place.

3. That temperature changes within the concrete or instrument may affect the results obtained.

4. That under conditions of unloading similar to the conditions of loading the hysteresis effect observed is not due to the behavior of the concrete.

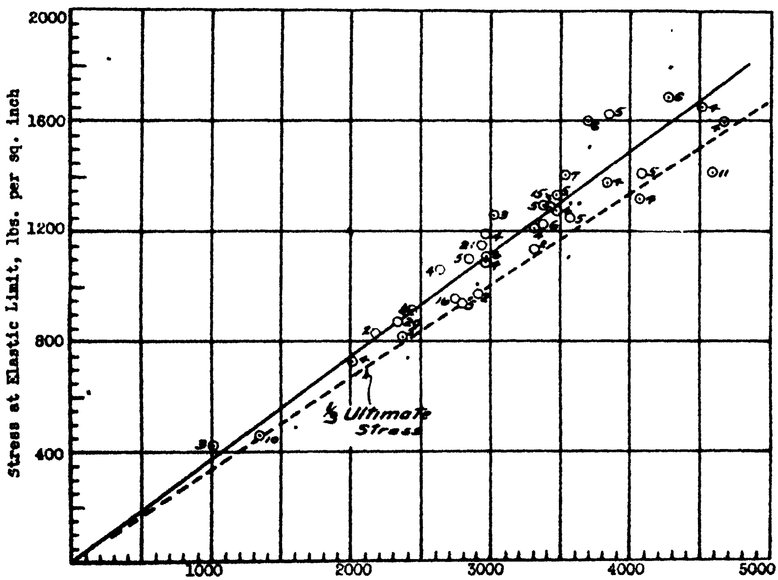

Figure 6.

THE RELATION BETWEEN ELASTIC LIMIT AND ULTIMATE STRESS

Figure 6 is a plotting of the elastic limit values of Table 1. Each circle represents the average value of the cylinders made from the same batch or under similar circumstances in the field. The number adjacent to each circle is the number of cylinders averaged to obtain the point. The dots that appear are for individual cylinders, each of which represents a mix as listed in Table 1. The solid line passes through the weighted mean of the points plotted. The dotted line represents one-third of the ultimate stress.

This graph shows a definite relationship between the ultimate stress and the elastic limit stress regardless of the conditions of tests as to age, source, mix, and method of testing. The elastic limit stress is, on the average, 37.5 percent of the ultimate stress.

The point that shows the greatest error is the point at a stress of 4600 pounds per square inch, and 1400 pounds per square inch elastic limit, an average of eleven cylinders (Nos. 78 to 88 inclusive) received from the field. The elastic limit value of this point is only 30.4 percent of the ultimate or below the curve by 18.3 percent.

As these cylinders have a very high ultimate strength, and as they were tested in the screw machine with fixed heads using plaster of Paris capping, the author feels that they would show a much smaller deviation from the mean if tested under the present procedure. In fact, fifteen cylinders (Nos. 218 to 232 inclusive) taken at the same time as the above eleven cylinders but tested six to eight months later and capped with Lumnite mortar and using spherical heads gave a point which does fall on the curve, although the ultimate stress is somewhat lower. Thus we see that the method of seating the cylinders is vital when accurate results are desired, especially when the concrete is comparatively strong.

THE RELATION BETWEEN ULTIMATE STRESS AND THE MODULUS OF ELASTICITY

There have been several attempts to relate the ultimate strength in pounds per square inch and the modulus of elasticity of concrete.

Mr Stanton Walker in Bulletin No. 5 concludes:[1]

"The modulus of elasticity of the concrete is a function of the compressive strength. The relation between modulus of elasticity and strength for mixtures leaner than about 1:3 may be represented by an equation of the form:

$E = C\,S^m$ where E=modulus of elasticity of concrete
C=a constant depending on the conditions of the tests
S=compressive strength of concrete and
^{m}=an exponent."

And, "For the tangent modulus at 25 percent of the compressive strength, the equation becomes

$$E_{t25} = 66000\sqrt{S}$$

Substituting in this equation we find that for

1000 lbs. stress per sq in.,	$E_{t25} = 2.085 \times 10^6$ lbs. per sq. in.
2000	$= 2.97$
3000	$= 3.59$
4000	$= 4.17$
5000	$= 4\ 64$

Dean A. N. Johnson, in his article on "The Modulus of Elasticity of Cores from Concrete Roads,"[2] makes this statement in regard to this relationship. " . . . .No marked relationship is found in these data between the crushing strength of the cores and the modulus of elasticity."

This statement is in regard to tests on 112 cores drilled from concrete pavements in Maryland.

Professor R. E. Davis and Professor G. E. Troxell[3] of the University of California in a paper read before the Thirty-second Annual Meeting of the American Society of Testing Materials shows data and results of tests of some 350 concrete cyinders. Under "Summary of Results" we find among others the following two statements·

[1] Page 50, Bulletin No. 5, Structural Materials Research Laboratory, Lewis Institute.

[2] Public Roads, October, 1928.

[3] Vol. 29, 1929, Part 2, Page 700.

1. "The secant modulus of elasticity decreases as the stress increases, but for the richer mixes the variation with stress becomes less as time goes on."

2. "There appears to be no direct relationship between modulus of elasticity and compressive strength which is generally applicable. But with conditions constant as regards aggregate, cement ratio and storage it appears in a general way the higher the ultimate strength the greater the secant modulus at a given stress."

Mr James W. Johnston in Bulletin No. 90.①, in a figure for concrete in compression where the modulus of elasticity is recorded for 50 percent of the ultimate stress of the concrete, shows a fairly definite relationship between the modulus of elasticity and ultimate strength, but separate and distinct curves for limestone coarse aggregate and gravel coarse aggregates. He also makes the following statement② regarding this strength-

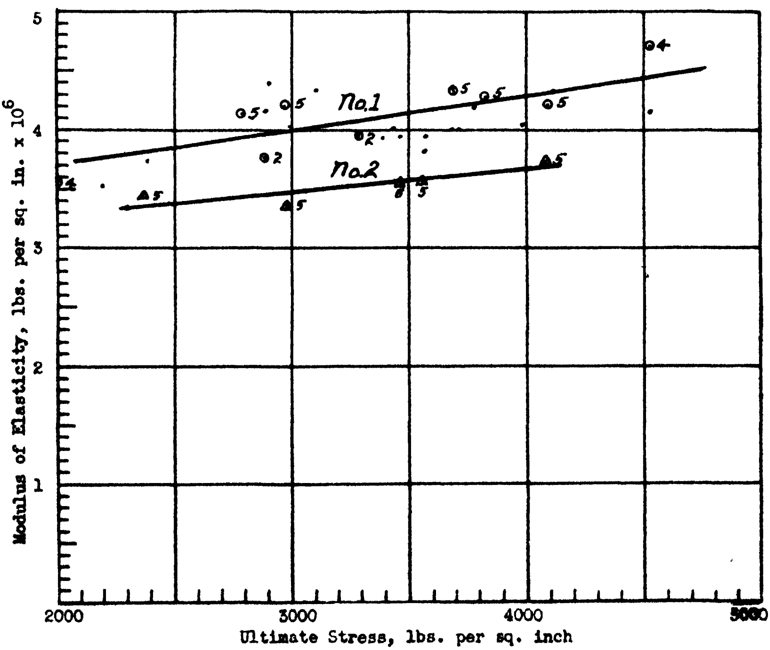

Figure 7.

① Engineering Experiment Station, Iowa State College.
② Page 33.

modulus relationship: "The strength-modulus relationship depends on the aggregate and cement used, and is different in tension and compression."

If all of the results of Table 1 are plotted between ultimate stress and modulus of elasticity at the elastic limit regardless of source, aggregate used, age, slump, and other factors which may have a bearing upon this relationship, there seems to be very little consistency found. If, however, the source is considered along with the aggregate, curves are obtained that do show a fair relationship.

Figure 7, Curve No. 1 is plotted from Table 1 for all the data obtained by students and from laboratory mixes when crushed basalt screened 1"—¼" and concrete sand No. 1 are used. Each point enclosed by a circle or triangle is the average of the number of cylinders indicated by the figure appearing adjacent to the point.

The dots appearing represent individual cylinders. For these cases there was only one cylinder taken from the batch, or else variations in age of the concrete did not allow averaging.

Because of lack of data below a unit stress of 2000 pounds per square inch a straight line has been drawn through the points shown. If other points were shown below this stress the line drawn through the points would probably assume a curved form.

These points are plotted regardless of mix, age, proportion of sand to gravel, slump, and method of testing. The maximum deviation from the curve shown by any point that is an average of several cylinders is 6.5 percent. In view of the above conditions this error is not excessive, especially when one considers that the results of other investigators referred to above show maximum errors of more than 10 percent when all conditions were controlled even to the extent of regarding the aggregates for each batch.

Curve No. 2, Figure 7, represents the tests of cylinders cast from batches made by students when constructing large reinforced concrete beams. It is customary to calculate sufficient material for the beam and five cylinders, then to mix the materials in a large wooden mixing bin and to fill the beam forms. After this the remainder was remixed by turning over once or twice, and the cylinder forms were filled in the customary manner.

Just why these points, the work of five different student sections, should fall below the work resulting from laboratory mixes and laboratory instruction is hard to explain. The materials are the same. The batches represented by the points for Curve No. 1 were only large enough to cast the number of cylinders indicated at each point. The batches were designed by using a definite water-cement ratio in each case and by the "Trial Method." The materials were mixed in a sheet iron tray using standard methods of manipulation.

The following reasons for the difference are suggested:

1. Standard laboratory methods of manipulation should give better results than when the batch is multiplied several times and conditions of manipulation approach those used in the field.

2. More uniform mixing of materials unconsciously obtained when working with small quantities in an iron tray as against large quantities mixed in a wooden bin on the floor using shovels

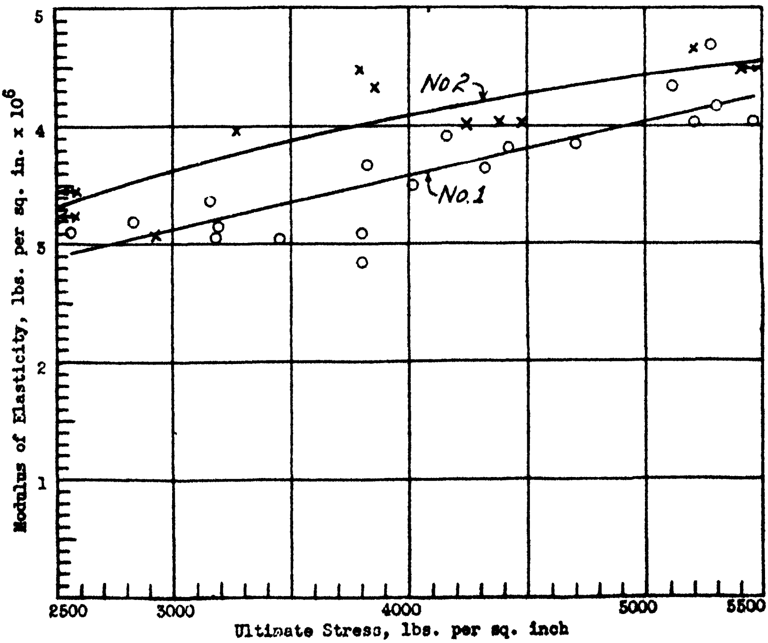

Figure 8.

Figure 8, Curve No. 1, shows the results of tests of individual cylinders received from a municipality covering the construction of a viaduct. The Materials Testing Laboratory had no control over the concrete used on this particular job, but did receive the vital data① in regard to materials used and the mixes, which varied with the various parts of the construction for Curve No. 1. For this curve the points shown are plotted without regard to age, mix, or slump. It is assumed that the method of curing is substantially the same for all of the cylinders, and the aggregate, both fine and coarse, did not vary as to source.

The cylinder showing the maximum error below Curve No. 1 showed an excessive accumulation of the maximum size of coarse aggregate when broken open after the test.

Curve No. 2, Figure 8, represents results obtained in testing cylinders resulting for street paving in the same municipality. They cylinders plotted are Nos. 233 to 238 and 260 to 265 inclusive. The vital conditions as to aggregate, mix, method of curing, and slump, are not known. The age at the test varies from 56 to 120 days.

Figure 9 is the plotting of cylinders Nos. 132 to 135 and 146 to 176 inclusive. Except for the design mix (cylinders Nos. 132 to 135 inclusive) these cylinders were obtained from a Campus construction job. A two sack mixer was used and two cylinders were taken each day of operation. A concrete buggy was side tracked by the inspector, a slump test made, and two cylinders poured. The cylinders were stored in damp sand until tested. Eleven cylinders, one for each day, were tested at an age of seven days while the other cylinder for the day was allowed to cure for twenty-eight days. From Table 1 it will be noticed that the slump values vary from 2½ inches to 7 inches and that the age varies from seven days to a maximum of forty-four days at testing.

The mix used was designed in the laboratory by the "Trial Method" The mix was transferred to the field by making the usual corrections for bulking due to moisture and loose measure. The water-cement ratio was not maintained on the job.

① Furnished by Mr. A. D. Butler, City Engineer, Spokane. Washington.

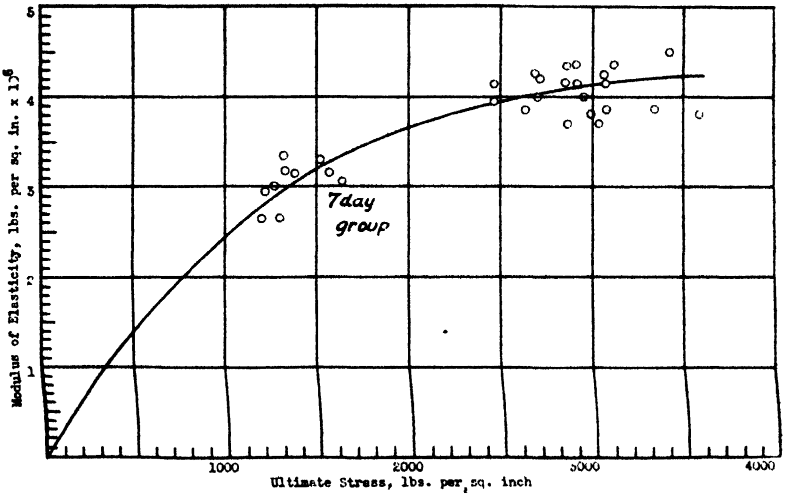

Figure 9.

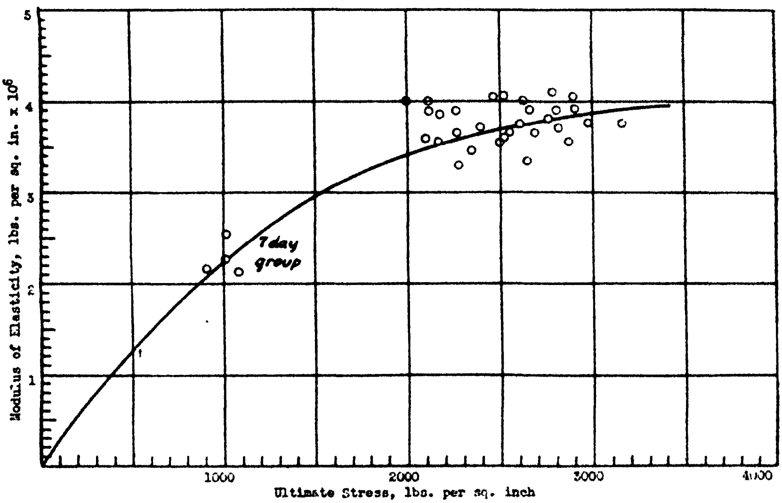

Figure 10

Figure 9 shows a fairly wide range in strength and a maximum deviation from the mean curve of less than 11 percent for any one point for the modulus of elasticity. In fact, the extreme percent range of values for the modulus is less than the percent range of strength. The seven-day relationship is distinctly lower than the twenty-eight day and older concrete. However, the modulus is influenced more by the strength obtained by the concrete when tested rather than the age at test.

Figure 10 is the plotting of the results obtained from the test of cylinders Nos. 136 to 145 and 177 to 217 inclusive. These cylinders were obtained from the same job under the same conditions as the cylinders of Figure 9 except 1½″—¼″ gravel was used instead of 2″—¼″ crushed basalt as a coarse aggregate. Cylinders Nos. 137 to 145 inclusive cover the laboratory design of the concrete. The remainder are from the field.

The results as to strength at seven days caused the mix to be changed during construction. Therefore the points are for two values of mix as

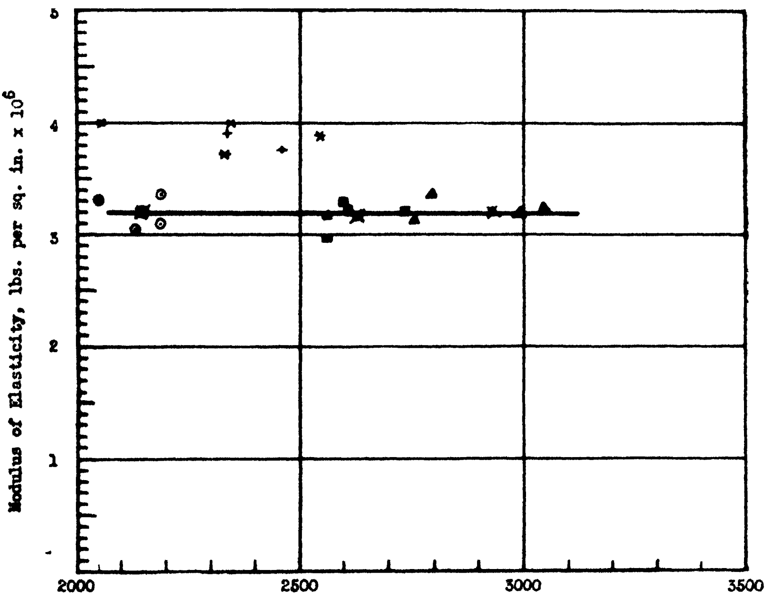

Figure 11.

well as for the various slump values and other variables as indicated under the material for Figure 9.

In the plotting of the points for both Figures 9 and 10 it was noticed that in almost all cases where the duplicate cylinders for any one day were tested at the same age the points plotted with the same value of the modulus although the strength values may have varied considerably.

Figure 11 is a plot of the data obtained from cylinders Nos. 239 to 259 inclusive. This concrete was made by the students in regular laboratory for constructing the reinforced concrete beam. The procedure was the same as for the points plotted for Curve No. 2, Figure 7, except in this case the coarse aggregate was changed from crushed basalt to 1½"—¼" gravel.

The points appearing in the group above the curve are for concrete made of the same materials but regraded according to Fuller's curve. Although the data is limited these points indicate that grading of the material used has an important effect on the modulus of elasticity of the resulting concrete.

SUMMARY AND CONCLUSIONS

It has already been stated that the data presented is a result of the various functions of the laboratory and not the result of a study designed and carried out expressly for the relationships that have been shown by the graphs already exhibited.

With this in mind we may be permitted to draw some definite conclusions while others should be verified by further study.

DEFINITE CONCLUSIONS

1. Concrete as tested at the State College of Washington is elastic in the same sense that we consider steel elastic.① Inelastic concrete is the exception and can be explained, for instance, by the improper grading of aggregate, (see cylinders Nos. 13 to 18) by improper procedure in mixing and forming of cylinders, or by improper methods of testing.

① The author makes this statement advisedly and is cognizant of the work accomplished in regard to plastic flow and creep in concrete and steel.

2. The elastic limit occurs at approximately 37 per cent of the ultimate stress. Beyond this point the curve bends off gradually until failure is reached.

3. The relation between the elastic limit and ultimate stress is fairly constant; as the ultimate stress is effected by the variable factors, so also is the value of the elastic limit.

4. As long as the elastic limit of the concrete is not exceeded concrete may be reloaded and the same stress-strain relations will be obtained upon the consecutive loadings as were obtained on the first loadings. (See Figures 4 and 5.)

5. The methods of bedding and applying loads to the cylinder along with accuracy and sensitivity of the testing machine and instrument have had, in the past, more to do with our present conception of concrete than other variables which are often given the credit for our changing conception of concrete. For instance, this laboratory three years ago did not find concrete elastic. During this period many conditions erroneously effecting the stress-strain relations have been discovered and eliminated. Some of them can be enumerated as follows:

a. Johnson type wire wound compressometer was found unsatisfactory thus leading to the development of a more sensitive and accurate compressometer.

b. Increments of loading so large that not enough points were established on the stress-strain diagram to be sure of results.

c. Use of testing machine that gave initial curvature of stress-strain diagram. See Figure 4.

d. Use of plaster of Paris and fixed heads. It was found necessary to eliminate plaster of Paris as a bedding material for all cases.

e. End cappings not flat by a few thousandths of an inch due to several conditions.

f. Eccentric loading of cylinders when placed in testing machine.

g. Temperature changes during test.

6. The value of the modulus of elasticity as determined by actual test is considerably higher than the value used in design especially for 2000, 2500, and 3000-pound-per-square-inch concrete.

7. There is a relationship between the ultimate strength and the modulus of elasticity if the data is grouped in relation to source.

CONCLUSIONS WHICH NEED ADDITIONAL VERIFICATION

1. The strength-modulus relation is affected by the type of coarse aggregate used; that is—basalt, gravel, limestone, etc.

2. The strength-modulus relation is affected by the grading of the aggregate, both fine and coarse. (See Figure 11.)

3. The strength-modulus relation is affected by the methods of manipulation when the concrete is made. That is, strictly laboratory procedure or conditions approaching those used in the field. (See Figure 7.)

4. There are conditions peculiar to each job in the field that affect the strength-modulus relation. These conditions no doubt include those already mentioned and perhaps conditions unknown at present

5. Where all variables are constant except the water-cement ratio and the attendant change in mix value, the strength may vary through a wide range with but slight change in the modulus of elasticity. (See Figure 7, Curve No.2, and Figure 11.)

The author feels that although the data presented were gathered from cylinders from many sources, the results as presented are quite uniform In fact they are as uniform and consistent as results presented by other investigators who have limited many variables which of course could not be done in this study.

If 10 percent of the erratic data could be eliminated from Table 1 then all the remaining values would check within 10 percent of the mean. In fact, during the present college year we have had very few cases where the cylinders from any one batch of concrete have had a total variation exceeding 10 percent.

It is quite certain that if cylinders recorded in Table 1 were to be tested with our present knowledge of laboratory procedure, less errors would show in the table.

The investigations will be continued and we hope to verify some of this work as well as add more information in the future.

Certainly accurate, economical, and safe concrete design cannot be had until we are sure of the physical properties of the main material that we are using in our structure.

VERIFICATION OF RESULTS BY USING INSTRUMENTS OF OTHER TYPES

A large amount of the data accumulated in the last few years concerning the physical properties of concrete has been obtained with the use of the mirror type extensometer. To eliminate question, a comparison between the results obtained with the hydrostatic and mirror type instruments is important.

A mirror type instrument was acquired for the laboratory after the data exhibited in Table No. 1 was completed so that comparison so far as concrete is concerned has been accomplished on additional cylinders that appear only in Table No 3.

Comparative tests have been made on both concrete and steel. A mild steel test bar was mounted in the 200,000 pound screw type testing machine for tension and upon the specimen were arranged four gages; namely, an H. C. Berry strain-gage, an Olsen "Last Word" extensometer, the mirror type instrument, and the new hydrostatic instrument. On the concrete cylinders, only the latter two instruments were used simultaneously.

In order that the results from the various tests could be visualized and comparisons made more readily the readings were plotted for each test.

When the stress-strain relationship for a material is a straight line the modulus of elasticity in a single factor expresses this relationship. The value of the modulus of elasticity for the steel bar as obtained by each instrument for stress up to 30,000 pounds per square inch is given in Table No. 3. It will be seen that there is a very close agreement between all instruments regardless of type, the only difference being a slightly higher value was obtained with the mechanical types and also the points as plotted indicate less accuracy than is shown by the hydrostatic and mirror types.

Four concrete cylinders of widely varying strength have been tested when using both the hydrostatic and mirror type instruments simultaneously. The comparative data for each cylinder has been recorded in Table No. 3. For cylinder C-1 a straight line was obtained for the stress-strain relationship from zero to a unit stress of 920 pounds per square

inch, when using the hydrostatic instrument. The mirror instrument in this case gave a curve from the origin which crossed the straight line given by the hydrostatic instrument at a unit stress of 700 pounds per square inch. The knife edges operating the mirrors were placed against the side of the cylinder on fairly rough surfaces, that is, grains of sand stood out from the surface and the knife edges had to fit in between these particles. This may or may not have been responsible for the obvious curvature obtained. In any event it is probable that this type of contact would not guarantee consistent results. In the following tests the knife edges were placed upon smooth surfaces on the concrete.

A study of Table No. 3 will show that for cylinder No C-2 both instruments recorded the same elastic limit stress but the stress-strain relationship curve assumed a slightly different slope for each instrument. This is shown by the values of the modulus of elasticity, the value for the mirrors being 4.8% lower than for the hydrostatic instrument. This is the maximum difference obtained in any of the verification tests. The readings for cylinders C-3 and C-4 checked so faithfully in all respects that no differences are recorded in Table No. 3.

Another indication of the faithfulness of the two instruments is in the fact that at 400 pounds per square inch stress in the concrete a slight change in slope occured in the stress-strain diagram. In all ordinary plotting of stress-strain diagrams this change of slope would not be found; however in the magnified plottings used for these comparisons this change in slope was found for three cylinders out of the four. The fact that both instruments recorded this point, that it occurred at 400 pounds per square inch regardless of the ultimate strength of the concrete, would lead one to believe that it was caused by some condition which was not a function of the concrete or of the compressometers.

As a result of the above verification tests several observations can be enumerated:

First: The fact that deformations in 6" by 12" concrete cylinders can be measured by increments of one millionth of an inch per inch with total errors not greater than 5% is particularly gratifying when one considers that the readings were arrived at with instruments altogether different in principle, construction, and method of calibration.

Second: When reading deformations in concrete to a high degree of accuracy, errors introduced by the testing machine, compressometer and the method of testing may influence the stress-strain relationship in such a way that erroneous conclusions regarding the concrete will be drawn.

Third: The scale readings on the hydrostatic instrument were more than double those obtained with the mirrors when a scale distance of 60 inches from mirror to scale was used.

Fourth: The hydrostatic instrument required but a fraction of the time for "setting up" in relation to the mirrors.

Fifth: In its present form the hydrostatic instrument is more sensitive to temperature changes than the mirror type; however, neither can be used in tests of the accuracy here described covering a long interval of time without requiring correction for thermal expansions.

Table 3.

Cyl. File No.	Instrument used	Material	Unit Stress Ult.	Unit Stress El. Lim.	E at El. Lim. $\times 10^6$	Diff. at Elastic Limit %
	Berry	Steel			30.1 *	
	Last Word (Olsen)	Steel			30.1	
	Hydrostatic	Steel			29.8	
	Mirrors	Steel			29.8	
C—1	Mirrors	Concrete	3030	Curve	3.75	
C—1	Hydrostatic	Concrete	3030	920	3.86	‡ 3.5%
C—2	Mirrors	Concrete	5160	1700	3.96	
C—2	Hydrostatic	Concrete	5160	1700	4.16	‡ 4.8%
C—3	Mirrors	Concrete	2470	990	3.34	
C—3	Hydrostatic	Concrete	2470	990	3.34	0.0
C—4	Mirrors	Concrete	6610	3000	4.61	
C—4	Hydrostatic	Concrete	6610	3000	4.61	0.0

* Modulus calculated at 30,000 pounds per sq. inch stress in the steel.

‡ The readings obtained with the hydrostatic instrument used as the base

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MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Volume 12 November, 1929 Number 6

SECOND PROGRESS REPORT

Rhythmic Corrugations in Highways

by

Homer J. Dana

Washington State Highway Department, Cooperating

ENGINEERING BULLETIN NO. 31
ENGINEERING EXPERIMENT STATION

January, 1930

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st, 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washintgon The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

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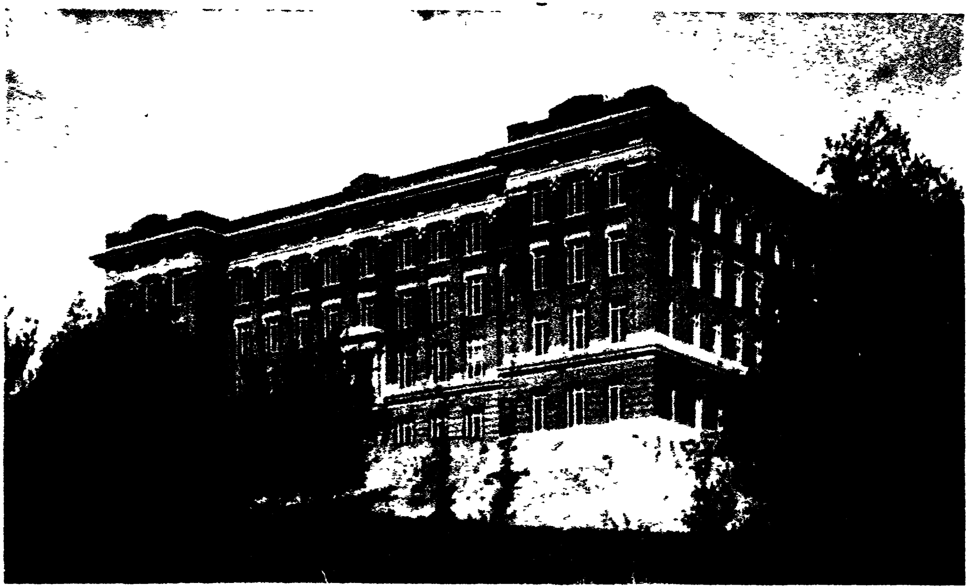

The Mechanic Arts Building, which Contains the Offices and Part of the Laboratories of the Engineering Experiment Station of the State College of Washington.

FORMATION OF WASHBOARDS IN GRAVEL HIGHWAYS

By

Homer J. Dana*

INTRODUCTION

Highway transportation in the United States is becoming more important and more popular each year In many places where the traffic will warrant the expenditure, hard surface roads have been built Whether or not a concrete or bitulithic road is built in a given locality is determined partly by the traffic need for such a road, and partly by the financial conditions and the political situation of that region as well In places where hard surface roads for one reason or another cannot be built, and traffic warrants an improved road, it has been customary to surface the road with gravel or crushed rock with which a small amount of clay is mixed for binder This is a type of macadam surface commonly found in the Pacific Northwest. There are thousands of miles of such highway in use throughout the United States with many additional miles being added each year

A crushed rock or gravel type surface when in good condition gives excellent service for both passenger and trucking traffic. However, as the volume of traffic reaches one thousand or more cars per day, such a surface quickly develops transverse corrugations which are commonly called "washboards". These are also known as rhythmic corrugations, ripples, chatter bumps, etc.

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* The Engineering Experiment Station wishes to express appreciation to the Hon. Samuel J. Humes, Director of the Washington State Highway Department, and to Mr. Geo. J. Beck and the late Mr. L. A McLeod, of the District office of the State Highway Department at Spokane for encouragement and assistance given toward conducting these tests during the summer of 1929.

The presence of "washboards" in gravel or crushed rock highways has proven to be a serious problem in many ways. For one thing, it increases the hazard of driving in that cars cannot be so well controled over such highways at high speeds. The severe treatment endured by the tires and running gear of the car tend to shorten the life of those parts materially. In the case of trucks, a badly "washboarded" highway tends to limit the maximum possible load which the truck's springs can carry. On account of these problems, the highway maintenance engineers have continuously sought means whereby they could either eliminate or materially diminish the formation of "washboards" in gravel highways. Their efforts have been directed primarily toward the treatment of the road surface, and this has been only partly successful. By. the use of intensive maintenance such as frequent planing and blading of the gravel surface, they have found it possible to limit the depth of "washboards" on such highways. However, the fact that, in order to plane down the "washboards", the road surface is being continuously stirred and pulverized by the maintenance equipment has augmented what has commonly been called the "dust menace" of driving and has resulted in a rapid loss of binding material carried away by the wind. For these reasons and in the interest of economy it is desirable if possible to learn if there might not be some better way of minimizing the "washboard" menace than by means of an intensive maintenance program.

With this situation in mind, the Engineering Experiment Station of the State College of Washington a number of years ago undertook a study of the cause and prevention of "washboards" in gravel highways. In 1926, a car was equipped with a recording mechanism which recorded on paper the relative motion of a car axle with respect to the body of the same car when traveling over "washboarded" roads. Extensive tests were made at different speeds over several different "washboarded" highways Tests were also conducted on perfectly smooth roads on which had been placed a bump or a single depression. This made it possible to analyze the entire history of a single road shock. It was soon apparent that in the making of these tests there were other factors besides the bumps on the road surface which were entering into the test record. One of these especially was the lurch of the car body from side to side.

During the following summer, namely: of 1927, a small laboratory apparatus was developed which embodied the characteristics of a car and on which tests could be made without the introduction of disturbing influences other than those being studied. All cars possess the characteristics of sprung and unsprung weight. The car body, which is carried on the springs is the "sprung weight". The car axle together with the hubs, brakes, and wheels constitute the "unsprung weight". This "unsprung weight" however, is somewhat cushioned by the air in the tires. By means of the above mentioned laboratory apparatus, careful analysis was made of the relative motion of the different parts of the car when subjected to "washboard" shocks at different speeds. The results of these tests were published in Engineering Bulletin No. 19.

In order to further study this problem, during the following summer of 1928, a test track was built on the State College campus for carrying on further "washboard" tests. This track was built 175 feet in diameter and banked for a normal speed of twenty miles per hour. The surface of the track was given a gravel topping according to standard highway specifications except that it was only about 5 inches thick. A model T Ford touring car, used for the test, was equipped with high pressure tires, namely, three and one-half inch tires at fifty-five pounds air pressure and driven at twenty miles per hour. "Washboards" could be formed on the gravel surface of the test track in 100 trips. Equipped with hydraulic shock absorbers, the formation of "washboards" was found to be much slower. In fact, it was not possible to make satisfactory "washboards" on the test track with this combination. When balloon tires were substituted, without shock absorbers, it was found impossible to make "washboards" on the test track, even though the test was continued until the road was virtually worn out.

While the above tests all contributed to the fund of information on the subject of "washboards", it was felt that further tests should be conducted on a straight highway. This would more nearly duplicate the conditions which exist on the public highways, and results from such tests would be more readily accepted by engineers and others interested in highway maintenance.

PART I

OBJECTS OF TESTS

The results of the foregoing tests and experiments would seem to indicate that there is a possibility of solving the "washboard" problem, in so far as it can be solved, not by attacking it from a maintenance standpoint but by controlling the conditions and characteristics inherent in the car itself. If this were possible, then at least part of the present objectionable and expensive method of continuously loosening the road surface would be eliminated. A reduction of this present maintenance program would save substantial amounts of maintenance money, which otherwise could be devoted to improving the highways. With these things in mind, the problem was laid before the State Highway Department of Washington. Later, with their cooperation, a stretch of gravel road was chosen and prepared for further tests during the summer of 1929.

IDEAL CONDITIONS FOR TESTS

During the long dry summers which are characteristic of eastern and central Washington, road surfaces become more or less thoroughly dried out. The dry clay binder which is made a part of the gravel and crushed rock highways found in this section loses much of its cementing value and fails under the force of heavy automobile traffic. The continued impact of automobile tires then loosens and moves this gravel surface into successive bumps and hollows. If this gravel is restored to a smooth surface by means of a drag or grader, an equal amount of traffic will again restore the "washboard" condition. For this reason, the dry summer weather of Eastern Washington makes it possible to duplicate conditions and repeat tests rapidly and with fair uniformity of results.

DESCRIPTION OF TEST ROAD

Out of several sites under consideration, one was chosen which is located about twelve miles southwest of Spokane. More particularly, this road was a part of the original highway between Spokane and Cheney before the new concrete road was built. It runs east and west on the east side of the concrete highway and one-fourth mile

north of Four Lakes, Washington. The road is level throughout its length except for a short section which has a grade of from three to four per cent. There are two long easy curves. The surface appears to be of screened material from a glacial gravel deposit, and it is estimated that eighty-five per cent of this loose material on this road would pass a three-eighths inch screen. The sand is quartz with practically no basalt present. During the season of the spring rains, the State Highway department went over this road with a grader and left it perfectly smooth. Under the normal light traffic (ten to fifteen cars per day), the surface became hard and smooth During the following dry weather, a grader was again used to plane the surface leaving about two inches of loose material on a perfectly smooth hard base

CONDUCTING TESTS

Preliminary to each test, this loose material was brought to the center of the road and spread evenly a little wider than the width of

Figure 1. The Road Drag, Used to Prepare the Test Road for the "Washboard" Test, Is Shown Lifted from the Road Surface to Reveal the Four "Edges."

a car. The drag used, (See Fig. 1 & 2) consisted of four angle-irons rigidly welded to cross-bars and dragged behind the car at about sixty degrees angle to the line of travel. After going over the road

with the drag in one direction, the angle of the drag was reversed on the return trip. This tended to eliminate "drag ripples" and left the road surface practically smooth and free of any bumps or depressions. See Fig. 3 & 4.

After a test had been completed, "washboards" would be present at various places on the road. See Fig. 5. Owing to the light traffic, the test car could be driven back and forth in the same track, thus concentrating all the travel on the center of the road. See Fig. 6 & 7. In order to thoroughly erase the influences of any previous test, the road was scarified each time before it was dragged. The scarifier

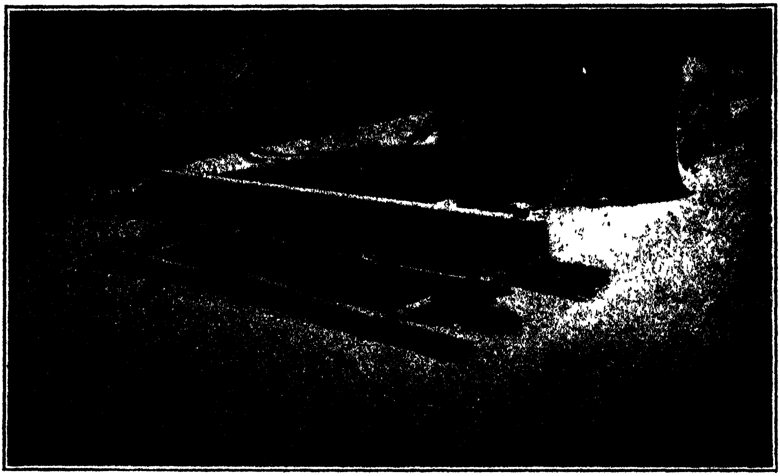


Figure 2. The Weighted Road Drag Attached to the Rear of the Test Car while the Road was Being Prepared for the Next "Washboard" Test The Blades of the Drag Make an Angle of About 60 Degrees to the Line of Travel.

consisted of a steel frame about eighteen inches wide and four feet long. See Fig. 8, 9, & 10. Four rows of teeth were arranged equidistant along the length of this frame. Successive rows of teeth were staggered with the preceding rows. While this scarifier was not heavy enough to actually tear up the hard surface of the road, it thoroughly loosened the gravel which the car had packed into "washboard" shape during the previous test. Thus after scarifying and dragging the surface for a new test, it was reasonably certain that the results would not be influenced by what had taken place previously.

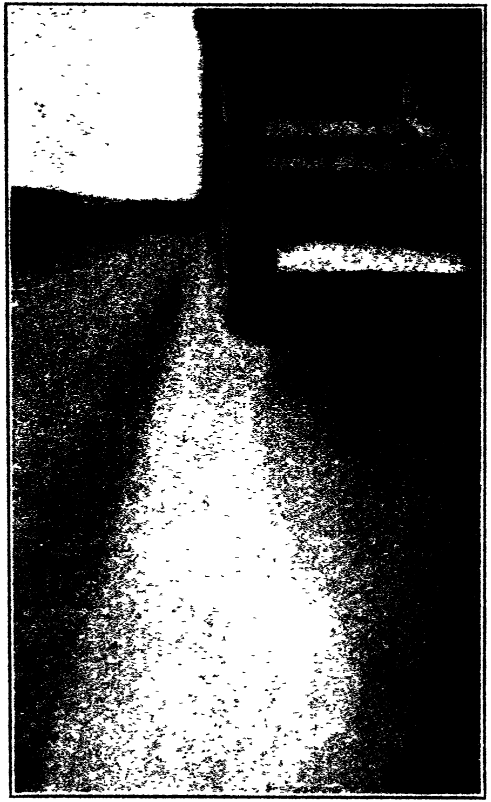


Figure 3. (Left) View of the Test Road on the 25 M.P H Section During Test with Balloon Tires

Figure 4 (Right) Note the Smooth Surface of Gravel Packed by the Balloon Tires No Evidence of ''Washboards'' on this 25 M P.H Section.

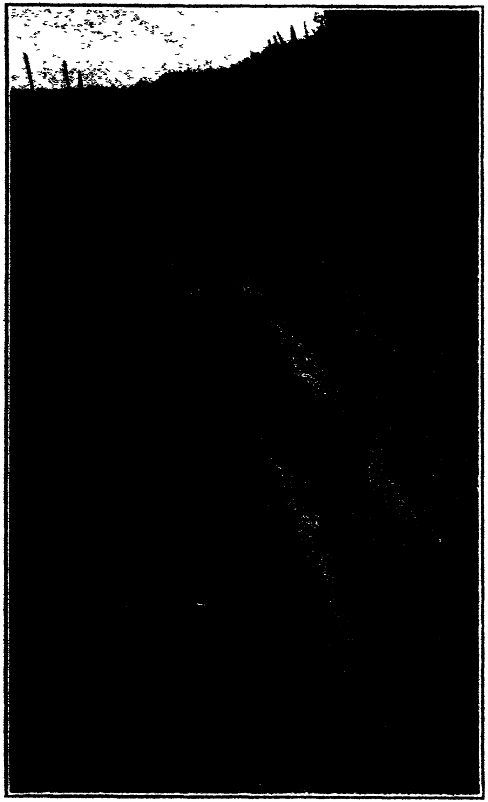


Figure 5. (Left) "Wash-boards" as Developed on the 35 M.P.H. Section, using High Pressure Tires.

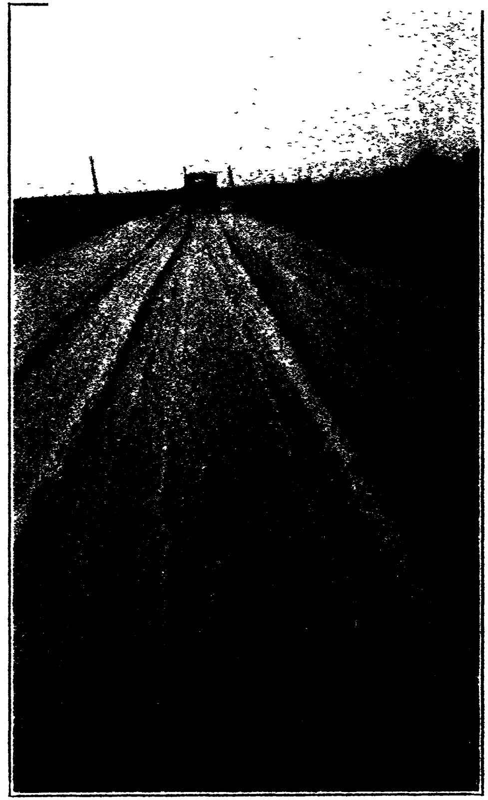


Figure 6 (Right) This Shows the Progress of the Test in the Loose Gravel on the 40 M.P.H. Section using Balloon Tires

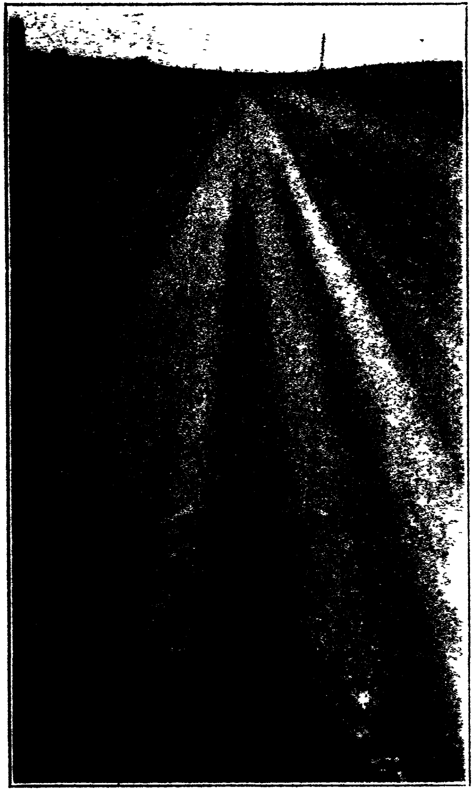


Figure 7 (Left) View on the 40 M P H Section Showing the Gravel Smoothed and Compacted by Balloon Tires

Figure 8 (Right) The Weighted Scarifier or "Plow" which was Used to Thoroughly Loosen the Compacted Gravel after each test

Figure 9. Quarter View of the Weighted Scarifier in Action, Erasing from the Road Surface, the Effects of the Previous "Washboard" Test

Figure 10. The Scarifier Raised from the Road Surface to Show the Four Rows of Teeth. The Teeth in Each Row Are Staggered with Respect to Those in the Preceeding Row. This View shows the Teeth Nearly Worn Out.

DESCRIPTION OF TEST CAR

It was deemed desirable that the car for these tests should be of medium size and weight. The car chosen was a 1927 Chevrolet Coach of 103" wheel base and weighing 2620 pounds with driver. Fig. 11. Two set of wheels were provided. On one set were mounted balloon tires, size 29 by 4.40, and operated at thirty-four pounds air pressure. On the other set of wheels were mounted high pressure tires, size

Figure 11. View of the "Highway Washboard Test" Car of the Engineering Experiment Station. The Car is Shown Equipped with High Pressure Tires A Set of Balloon Tires Were also Provided for the Same Car

30 x 3½ and operated at fifty-five pounds air pressure. The car was equipped with a new set of "TWO WAY" hydraulic shock absorbers Fig. 12.

DESCRIPTION OF TESTS

The test road which was one and four-tenths miles long was divided into five sections. On the section at one end of the road a speed of twenty-five miles per hour was maintained in either direction. On the adjacent section, the speed was raised to, and maintained at, thirty-five miles per hour. On the next section, at forty miles per hour; on the next section, at thirty miles per hour; and on the other end section, twenty-five miles per hour. At each end of the track, a

short section was reserved for decelerating prior to turning around and for accelerating again to twenty-five miles per hour. Also between adjacent sections, it was necessary to reserve a short distance for accelerating or decelerating for the speed in the next section. Thus, when the test was completed comparative results were shown at four different speeds.

At the beginning of the test, several days were spent in learning how to develop and control the desired conditions. For instance, it was found that dragging must be done at a speed not exceeding three to four miles per hour otherwise the drag would jump and chatter, leaving a rough surface It was also found that unless the angle of the

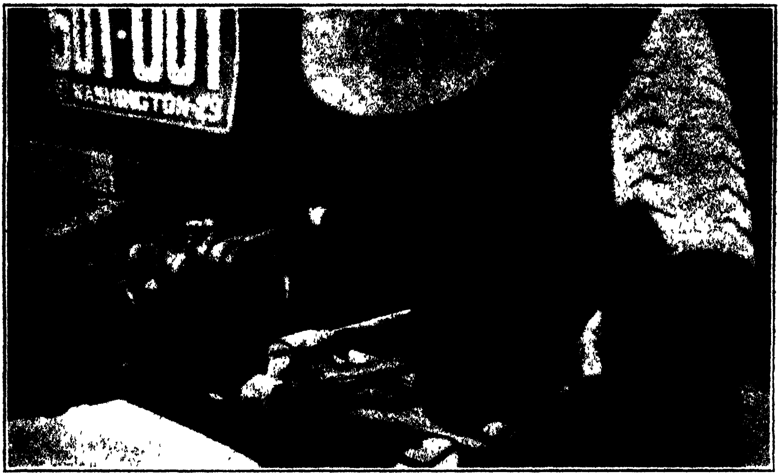


Figure 12. The Test Car was Equipped with a Set of Four "Two-Way" Hydraulic Shock Absorbers for the "Washboard" Tests.

drag to the line of travel was reversed each time over the road, a series of drag ripples would result which would seriously influence the results of the tests. Repeated tests were made during these first days until it was felt that the conditions were understood and could be controlled and duplicated at will. This made it possible to put the track in the same shape for each successive test. Furthermore, it was discovered that the formation of "washboards" as far as comparative tests were concerned need not progress to the extreme con-

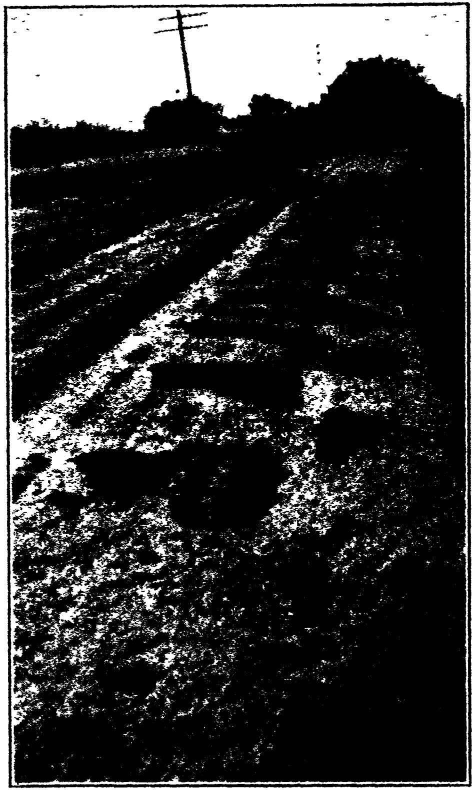
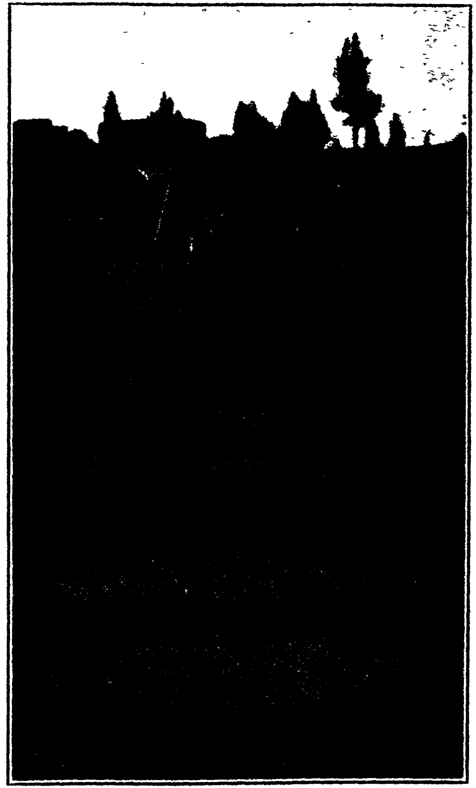


Figure 13 (Left) View of a Badly "Wash boarded" Section of Gravel Highway about Three Weeks after the Surface Had Been Treated with Oil. The Surface of the Rest of the road is smooth and hard

Figure 14. (Right) "Washboards" formed in dry Loose gravel The Base was Hard and Nearly Smooth, with humps of fine and coarse material more or less compacted into corrugations but still loose enough to be easily scuffed with the foot



ditions found on average gravel highways. In other words, a stopping point for the tests was determined upon in which the "washboards" were perhaps not more than one-eighth of an inch deep, and had not dug into the hard road surface. They consisted entirely of the loose gravel placed and packed in more or less uniformly spaced shallow ridges and hollows. At this stage of their formation, the "washboards" were plainly visible to a driver in a car, and the distance between successive ridges could readily be marked and measured.

The driver of the test car was constantly on the alert during the progress of the test to observe the first appearance and location of "washboards". Note was made of the time of occurence and the section of the road on which "washboards" first appeared. As might be predicted, "washboards" first appeared on the highest speed section, and were last to appear on the lowest speed section. Furthermore, it was observed that the average length of "washboards" varied according to the speed of travel on that section.

Figure 15. "Washboards" in an Oiled Gravel Highway. The Bumps are Hard and About One Inch High, and Were Formed by the Tires Digging Pits into the Smooth Hard Surface of the Road. Only a Very Small Amount of Loose Gravel is Present.

RESULTS OF TESTS

The following Table 1 shows the summarized results of the tests on high and low pressure tires with and without shock absorbers. The shock absorbers used, Fig. 12, were installed and used with the original factory adjustment which gives slight resistance to compression and considerable resistance to recoil.

While tests could have been made with other adjustments of the shock absorbers it was felt that other means could be devised for determining the optimum adjustment without spending the days and weeks necessary to conduct the road tests. In Table II are shown the average lengths of the washboards as measured on the different speed sections of the track. In Fig 13, 14, 15, and 16, are shown some typical washboards found on other highways during the summer of 1929. They average about 1" in depth and 27.5" in length. In Fig. 17 are shown the curves giving the information contained in Table I.

Table 1

Formation of W. B. as related to Speed of Travel on Test Track, 1929

Test No	Type Tire	Shock Absorbers	Trips to Make "Washboards" 25 MPH	30 MPH	35 MPH	40 MPH
1	H.P.	No	100	91	36	36
2	H.P.	No		No	results	
3	H.P.	No	137	79	71	65
6	H.P.	No	146	76	60	50
5	H.P.	Yes	290*	230	153	230
7	H.P.	Yes	188	188	105	92
9	H.P.	Yes	350*	220	126	110
4	L.P.	No		No. W. B. up to 360 trips		
8	L.P.	Yes		No. W. B. up to 570 trips		

CONCLUSIONS

From Table I it will be seen that speed of travel bears a definite relation to the rapidity with which "washboards" are formed by high

End of test with no washboards showing on this section.

pressure tires. Furthermore, the addition of one type of shock absorber at least has a retarding effect on the formation of "washboards" and would seem to prevent their formation at low speeds. It will be noted that in these tests, balloon tires did not make "washboards" even after prolonged operation on the test track. Whether or not, balloon tires would promote or retard their formation on an already, deeply "washboarded" highway is a question yet to be answered. Likewise, the comparative effectiveness of the different types of snubbers and shock absorbers is still to be determined.

Figure 16 "Washboards" in Loose Dry Gravel They Are about 1 Inch High and Are of Loose Material which can be Scuffed Away with the Foot

Table II

Characteristics of W. B. made on Test Track, 1929

Speed M.P.H	Average length of W.B. in inches	Number W.B. passed per second
25	21.14″	20.8
30	23.83″	22 1
35	26.47″	23.3
40	29.32″	24.0

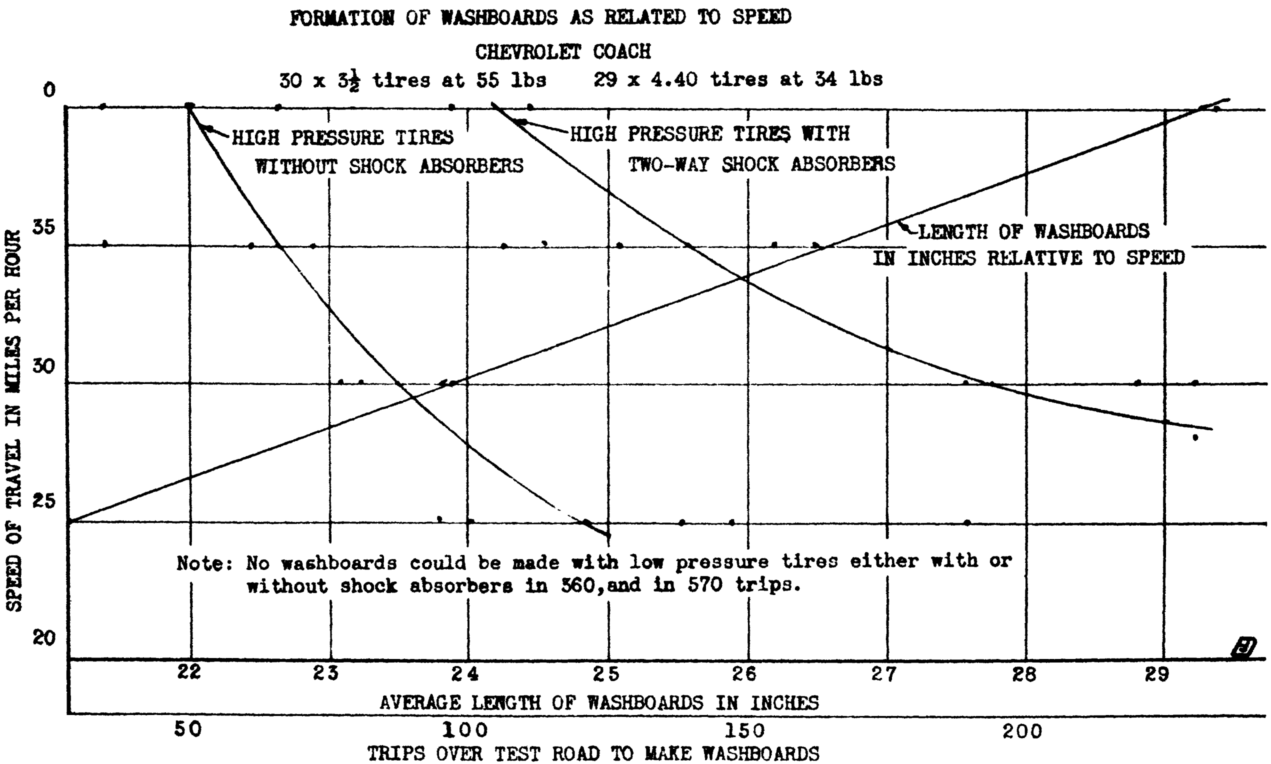


Figure 17. The Results of the 1929 "Washboard" Tests Given in Table 1 are Shown Graphically.

From Table II it will be noted that the average length of "washboards" in the different speed-sections varies somewhat according to the speed of travel of the car used in the tests, and this is to be expected. If the movement of the wheels and axles had corresponded with the free movement of a weighted spring, then the third column would have shown one constant value as the rate of vibration regardless of speed of travel of the car. The actual vibrations as computed from the average length of the "washboards" and the speed at which they were formed gives values ranging from 20.8 to 24.0 vibrations per second. This would seem to indicate that the speed of travel of the car introduces certain factors which cause the wheels and axles to vibrate at a higher rate at high speeds than at low speeds.

While the percentage of high pressure tires on passenger cars has greatly diminished and is at present very small, the percentage of trucks on the highway is constantly increasing. Truck tires are, at present, essentially of the high pressure type, although a very few trucks are using what is known as the truck type balloon. Most truck tires are operated at approximately 100 pounds air pressure which, together with heavy loads and relatively high speeds, would cause a more violent reaction upon the road surface than in the case of the above tests with 55 lb. tires. It is hoped that subsequent tests in the laboratory and on the highway will yield definite information as to how much the behavior of the car or truck wheels can be controlled with reference to its propensity for making "washboards". We have found much evidence showing that snubbers or shock absorbers applied to the high pressure type of tires will not only contribute to the easier riding quality of the vehicle thus equipped, but will serve to diminish the expense of maintenance both of the road and of the car. Such an accomplishment would point the way to a possible saving in maintenance money in the State of Washington alone of many thousands of dollars per year.

PART II

STUDY OF TEST CAR

In order to more correctly interpret the results of the tests described above, an intensive study was made of the behavior of the test car itself.

A rotating cylinder was mounted in the car and geared to the speedometer drive. This cylinder carried a blank paper record, on which two pencils were arranged to record the relative motion between the front and rear axles and the car body. Motion was conveyed to these pencils by means of steel piano wire run over pulleys and attached as near as possible to the right hand wheels of the car. The wire was attached to the pivot pin on the right front axle and to the brake housing on the right rear axle, both points of attachment being about the same distance from the plane of the tire.

With the above equipment, the test car was driven over a smooth and hard gravel highway, at one point of which had been placed a rounded artificial bump 6 inches wide and 1½ inches high. This was placed in the path of the right hand wheels only Records were made of the relative motion of the axles with respect to the car body at 20, 25, 30, 35 and 40 miles per hour, using high pressure tires, and low pressure tires, both with and without two-way hydraulic shock absorbers. These records are shown in Fig. 18 and Fig. 19.

ANALYSIS OF RECORDS

A general inspection of these records reveals that the use of shock absorbers either with high pressure tires or with balloon tires not only quickly damps out the axle vibrations but also reduces their amplitude of vibration. This means that the tire itself takes more of the shock, due probably to the fact that the reduced recoil of the springs by the snubber action of the shock absorbers causes the car body to ride lower with reference to its axles on "washboarded" roads. This perhaps is one of the things which influences the increasing of the rate of vibration of the axles with an increase of speed of the car, as indicated in Table II.

The records also show that the rate of vibration is higher for the front axle than for the rear axle. For instance, in Fig. 19, at 40

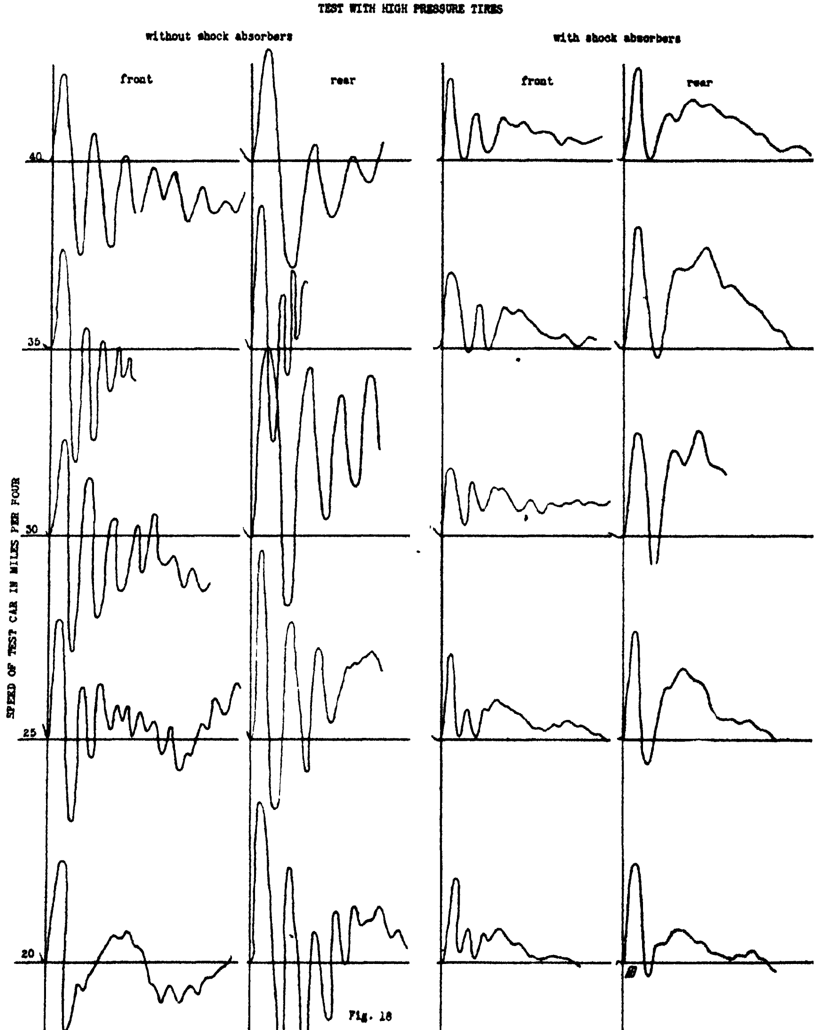


Figure 18 Relative Motion Between the Axles and the Body of a Car Equipped with High Pressure Tires and Travelling at Different Speeds over a Single Obstruction in a Relatively Smooth Gravel Highway.

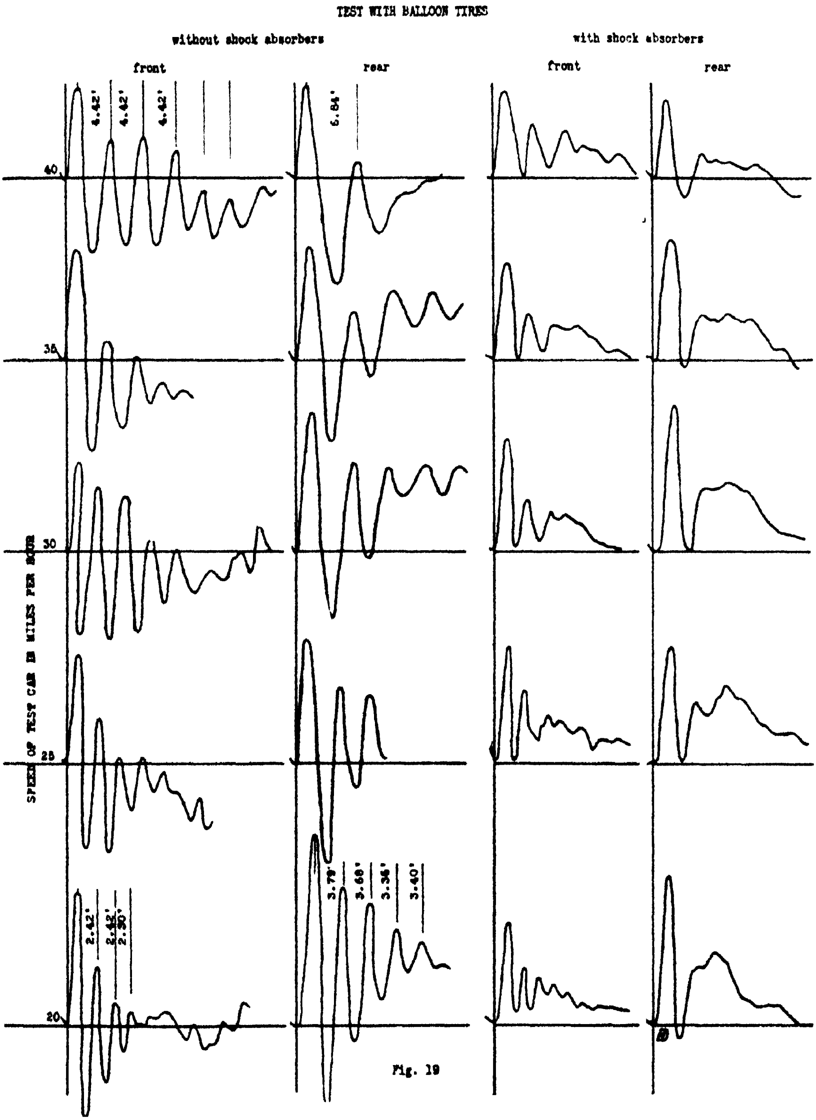


Figure 19. Balloon Tires Were Substituted for High Pressure Tires and the Tests Shown in Figure 18 Were Repeated.

M.P.H. the rate of vibration beginning with the first recoil is calculated to be 13.25 per second for the front axle and 8.57 per second for the rear axle. The amplitude with respect to the car body of the first vibration upward after striking the obstruction is 1.25 inches front and 1.25 inches rear at 40 M.P.H. This amplitude increases with decrease of speed showing that the tire absorbs more of the road shock at high speeds.

Also, from Fig. 19, at 20 M.P.H the rate of vibration is 12.2 per second for the front axle and approximately 7.9 per second for the rear. The amplitude with respect to the car body of the first vibration of the axle upward after striking the obstruction is 1.81 inches front and 2.57 inches rear at 20 M.P.H.

From the above it will be noted that the apparent distance between impacts of the tire on the road surface after striking the single obstruction exceeds the average length shown for corresponding speeds in Table II.

In this connection, consider Fig. 20, which represents the action of the axles of the test car travelling at 20 M.P.H. over "washboarded" highway where the average length of the "washboards" is found by measurements to be 23.9 inches. Neither the front axle nor the rear axle are oscillating in step with the "washboards" being travelled over, although both are not far from synchronism. From Fig. 21, where the car is travelling at 30 M.P.H, the front axle is shown to be oscillating practically in synchronism with the "washboards" being traveled over; and the curve is remarkably regular. On the other hand, the rear axle is oscillating more or less independently of the "washboards" and at a slower rate. When the axle vibration does correspond with a "washboard," then the reaction is indicated by a peak in the curve higher than the average.

From the information secured thus far, it would appear that the average length of the "washboards," formed on each section of the test track as shown in Table II, must represent a compromise between, or a combination of, the separtate forces exerted on the road surface by the two vibrating axles of the car, and therefore does not correspond to the natural period of either. This indicates that further study is necessary in order to fully understand the relation between cause and effect.

TEST WITH HIGH PRESSURE TIRES ON A WASHBOARDED HIGHWAY

with shock absorbers

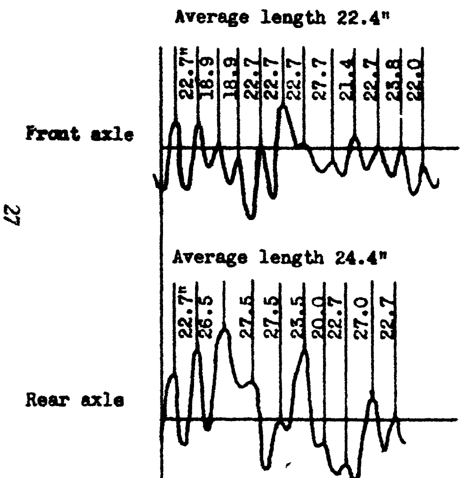


Fig.20

	Length of "Washboards" as measured
	26"
	21
	22
	19
	20
	24
	24
	27
	25
	24
	24
	23
	31
	23
	26
Average	23.9"

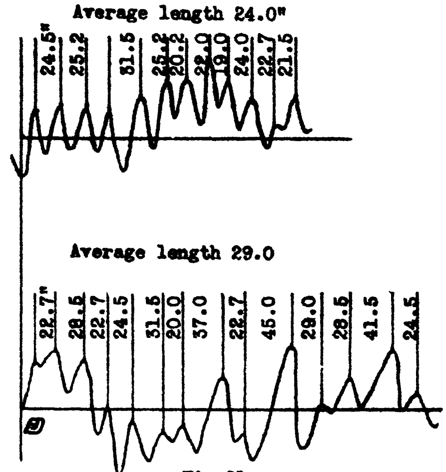


Fig.21

OUTLINE OF FURTHER STUDIES

The data thus far secured seems to indicate that there are a number of questions relative to the prevention of "Washboards" which are yet to be answered. For instance, will balloon tires driven over a badly "washboarded" highway tend to build up or tear down the existing "washboards"? Will the addition of shock absorbers to a balloon equipped car change the answer to the above question?

The results of all previous tests indicate that high pressure tires are far more destructive of gravel road surfaces than are balloon tires Since high pressure tires on passenger cars are fast disappearing, our attention is necessarily directed toward high pressure tires on trucks. This type of traffic is rapidly increasing both in weight and numbers. Much of the stage traffic would be classed with trucks as regards the high pressure tires. The question is, what is the relative effect of this type of traffic upon the highways considering the load per square inch of tire contact with the road surface (which equals the tire pressure) and the customary speed of travel.

In the light of the tests just concluded, at least one particular type of shock absorber (when applied to a passenger car) serves to delay the formation of "washboards" on gravel highways.

The question is, what type of shock absorber is most efficient in the prevention of "washboards"? Furthermore, to what extent can the formation of "washboards" be controlled by the application of such shock absorbers to trucks and stages equipped with high pressure tires? And again, is it possible that a more efficient type of shock absorber can be developed which will not only give riding comfort, but will be more effective in the prevention of "washboards"?

These and other kindred questions have presented themselves in the course of this investigation and the Engineering Experiment Station proposes a continued study of this problem which will ultimately embrace all the questions mentioned above. This will involve an intensive laboratory study of the inherent characteristics of different cars, to be followed by intensive tests on certain standard gravel highway surfaces. As rapidly as time and finances will permit it is proposed to carry this problem to completion.

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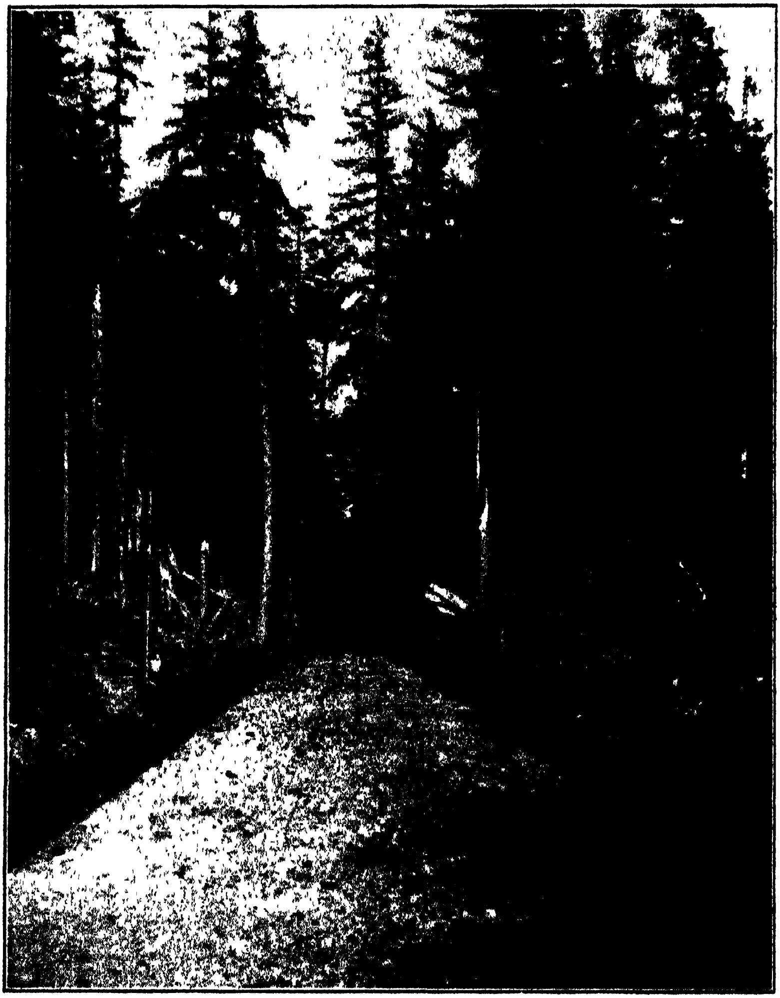

The constant demand for improved highways, and the yearly increase in traffic thereon, have given rise to constantly increasing maintenance costs. The study of "washboards" in gravel highways is just another attempt of the engineers to reduce this cost and improve the service of such highways to the public.

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 12 February, 1930 No. 9

The Economical Distribution of Steam in District Heating

by

A. C. Abell

ENGINEERING BULLETIN NO. 32

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission "to further the application of the principles of physical science to industrial pursuits." The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Popular bulletins are available as listed on pages 21 and 22.

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The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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THE ECONOMICAL DISTRIBUTION OF STEAM IN DISTRICT HEATING

By A. C. Abell

It often becomes necessary, in planning district or institutional heating systems to determine the relative costs of transmitting steam at different pressures, and with different allowable drops in pressure per 100 feet of line. Usually the solution of problems of this kind can be more readily accomplished if the relationships among the several variables, affecting the solution, can be expressed graphically. It is the purpose of this paper to develop these relationships together with charts for the solution of types of problems commonly arising in practice.

The delivery charges, in a district heating system, will include the losses of heat consequent upon the transmission, and the fixed charges on the pipe line. Since the cost of the conduit, whether it be subway, woodcasing, or tile construction, will vary with every locality and design, it has not been considered in the present calculation. The heat losses, which occur in a pipe line per unit of length, vary with the size of the line, the temperature difference between the pipe and the surrounding air, and the efficiency of the pipe covering.

COSTS

The cost of the pipe line in place is composed of the cost of the pipe and fittings on the job, the cost of the pipe covering, plus the cost of placing. The cost of the pipe, fittings and covering were taken, for this calculation, at the price to the trade. The cost of erecting was figured on the basis of one steam fitter and the necessary helpers, at the going wage, of \$8.00 and \$4.00 per day respectively.

The charges on the cost of pipe line will be made up of the following items, taken at the values given:

1. Interest on investment 7%,
2. Taxes at 2%,
3. Depreciation at 4%.
4. Maintenance at 2%.

On the basis of the above, the costs of different sized pipe lines in place have been calculated and are shown in Table I.

TABLE I

Cost of Pipe Lines in Place, per 100 Feet.

Pipe Size	Cost of Pipe per 100' on the Job Dollars	Cost of Service Fittings		Labor of Placing, Dollars	Cost of Std., 85% Magnesia Covering		Total Cost of Pipe Line Dollars
		% of Cost of Pipe	Dollars		on the Job	Cost of Placing	
3	$ 49.10	20 %	$ 9.80	$ 2.95	$27.00	$2.50	$ 91.35
4	74.35	17½ %	13.00	3.70	36.00	3.00	130.05
5	114.10	15 %	17.10	5.70	42.00	3.50	182.40
6	148.00	15 %	22.00	6.60	48.00	4.00	228.60
8	218.70	12½ %	27.20	8.80	49.50	4.50	308.70
10	315.95	10 %	31.60	9.50	58.50	5.50	421.05
12	415.55	10 %	41.50	10.40	83.20	6.00	556.65

Expressing the costs of pipe lines, as shown in Table I, on the basis of cost per pound of bare pipe, the results will be as shown in Table II.

TABLE II

Costs of Pipe Lines per Pound of Bare Pipe

Pipe Size	Weight Per 100 Feet of Bare Pipe	Total Cost of Pipe Line in Place	Total Cost Per Pound of Bare Pipe, in Place
3	761 6lb	$ 91.35	12 c
4	1088.9	130.05	11.95c
5	1481.0	182.40	12.28c
6	1918.5	228.60	11.92c
8	2500.0	308.70	12.34c
10	3200.0	421.05	13.10c
12	4500.0	556.65	12.35c

From Table II, it is seen that the cost of pipe lines, in place, is very close to 12 cents per pound of bare pipe, regardless of the size. This suggests that the annual fixed charges against the pipe line may be expressed by an equation of the form,

$$\text{Fixed Charges} = I\ K\ W \tag{1}$$

where

I = the sum of interest, taxes, depreciation and maintenance, expressed as a per cent of the cost,

K = cost of pipe line, per pound, in place,

W = weight of pipe, per 100 feet.

The capacity of pipe lines, in pounds of steam per second, is given by the relation:*

$$\text{Capacity} = K' \sqrt{\frac{P\ w}{L}} \tag{2}$$

where K' = Constant = 550 for a 12" pipe

350	,, ,, 10"	,,
195	,, ,, 8"	,,
97	,, ,, 6"	,,
60	,, ,, 5"	,,
32.5	,, ,, 4"	,,
15.5	,, ,, 3"	,,

P = total allowable pressure drop for the pipe line,

w = mean density of the steam, lbs. per cu. ft.

L = length of the pipe line in feet.

The fixed charges, per 1000 pounds of steam delivered, assuming 100% load factor, may now be expressed:

$$\text{Fixed Charges} = \frac{I\ K\ W\ 1{,}000}{365 \times 24 \times 60 \times 60\ K' \sqrt{\frac{P\ w}{L}}}$$

$$= \frac{0.0000317\ I\ K\ W}{K' \sqrt{\frac{P\ w}{L}}} \tag{3}$$

* Spitzglas, see, Gebhardt, Steam Power Plant Engineering Steam Boiler Engineering, Heine Boiler Company.

As the basis for plotting a diagram to represent Equation (3), assume the following values:

$$I = 15\%$$
$$K = 12c$$
$$\frac{P}{L} = \frac{1}{100}$$

Substitution of the above values in Equation (3) gives.

$$\text{Fixed Charges} = \frac{0.15 \times 12 \times 0.0000317\ W}{K' \sqrt{\dfrac{w}{100}}}$$

$$= \frac{0.000572\ W}{K' \sqrt{w}} \qquad (4)$$

Assuming different values of the mean pressure of transmission and substituting the corresponding values of mean density "w" in Equation (4), gives the results shown in Table III. These results have been plotted and are shown in Fig. 1.

For other values of the variables I and K the fixed charges will vary directly with the values of I and K and may be easily calculated. When the pressure drop, per 100 feet of pipe, is different than one, as here assumed, the fixed charges will vary inversely as the square root of the pressure drop used. This correction may be read from the diagrams.

Correction factor. A line marked "Correction Factor Curve" has been added to the diagrams, Figures, 1, 2 and 3, from which a factor may be determined with which to multiply the fixed charges, as read from the diagram, in order to correct for different pressure drops. For instance, suppose an allowable pressure drop of 0.3 of a pound per 100 feet of pipe is all that can be permitted. Enter the diagram at 0.3 on the pressure drop scale, pass vertically upward to the correction factor curve, and then to the left hand scale. The correction factor for this case is 1.83. That is, the fixed charges, per 1000 pounds of steam delivered, thru 100 feet of pipe, will be 1.83 times as much as that read from the diagram.

TABLE III

Nominal Pipe Diameter Inches	Weight of Pipe per 100 Feet, Pounds	K′	Fixed charges per 100 feet of pipe line, per 1000 lbs. of steam delivered, for a load factor of 100%			
			Mean Pressure =20 lbs. per sq. inch absolute w=0.0498	Mean Pressure =50 lbs. per sq. inch absolute w=0.1175	Mean Pressure =100 lbs. per sq. inch absolute w=0.2258	Mean Pressure =200 lbs. per sq. inch absolute w=0.487
3	761.6	15.5	0.126c	0.082c	0.0590c	0.0424c
4	1088.9	32.5	0.086	0.0556	0.0400	0.0288
5	1481.0	60.0	0.063	0.0411	0.0298	0.0214
6	1918.5	97.0	0.050	0.0330	0.0238	0.0171
8	2500.0	195.0	0.0328	0.02135	0.0154	0.0110
10	3200.0	350.0	0.0234	0.0152	0.0110	0.00788
12	4500.0	550.0	0.0190	0.0125	0.0090	0.00647

HEAT LOSSES

The heat losses from a pipe line, as has been stated, vary with the size of the line, the temperature difference between the pipe and the surrounding air, and the efficiency of the pipe covering. The heat loss from a bare pipe may be expressed as follows:

$$\text{Heat Loss (bare pipe)} = C\ A\ (T_s - T_a) \qquad (5)$$

where

C = coefficient of heat transfer, b.t.u. per sq. ft., per hour,

A = outside surface area of the pipe, in sq. feet,

T_s = temperature of the steam, deg. F.,

T_a = temperature of air surrounding pipe, deg. F.

If the efficiency of the pipe covering used, be denoted by "E", the heat loss from the covered pipe will be given by

$$\text{Heat Loss (covered pipe)} = C\ A\ (T_s - T_a)\ (1 - E) \qquad (6)$$

Since in most applications of steam, in heating work, only the latent heat of the steam is considered as being available, the losses expressed in pounds will be

$$\underset{\text{(covered pipe)}}{\text{Loss in pounds of steam}} = \frac{C\ A\ (T_s - T_a)\ (1 - E)}{L'} \qquad (7)$$

where L' = the latent heat of steam at the pressure of transmission

Assuming that standard 85% Magnesia covering is used, allowing "A" to be the area of one linear foot of pipe, then $(C\ A) = C'$ will be the loss per linear foot of bare pipe, per degree difference in temperature between steam and the surrounding air. Substituting this in Equation (7) gives,

$$\text{Loss in pounds of steam (covered pipe)} = \frac{C'\ (T_s - T_a)\ (1 - E)}{L'} \qquad (8)$$

The annual loss for 100 feet of pipe and 100% load factor will be given by the following relation:

$$\text{Annual loss in pounds} = \frac{365 \times 24 \times 100\ C'\ (T_s - T_a)\ (1 - E)}{L'} \qquad (9)$$

When the market value of steam is $1.00 per 1000 pounds, the loss per year, in dollars, will be

$$\text{Annual Loss, dollars} = \frac{365 \times 24 \times 100 \times 1 \times C'\ (T_s - T_a)\ (1 - E)}{1{,}000\ L'}$$

$$= 875\ C'\ (T_s - T_a)\ (1 - E)/L' \qquad (10)$$

Obtaining the yearly capacity of the pipe line from Equation (2) and dividing Equation (10) by this yearly capacity, gives the loss per 1000 pounds of steam delivered.

$$\text{Loss in 1,000 pounds of steam delivered, dollars} = \frac{875\ C'\ (T_s - T_a)\ (1 - E)\ 1{,}000}{365 \times 24 \times 60 \times 60\ K' \sqrt{\dfrac{P\ w}{L}}\ L'}$$

$$= \frac{0.0278\ C'\ (T_s - T_a)\ (1 - E)}{K' \sqrt{\dfrac{P\ w}{L}}\ L'} \qquad (11)$$

Assuming, as before, the value of $P/L = 0.01$ and that the temperature of the air surrounding the pipe is 80° Fahr and solving Equation (11) with different values of the mean density "w", the results shown in Table IV are obtained

TABLE IV

Losses in Cents per 1,000 Pounds Steam Delivered for 100 Feet Pipe Line 100 Per Cent Load Factor

Pipe Size	$(T_s—T_a)C'$	(1—E) *	K'	$\sqrt{w}$	L'	Loss per 1000 lbs. Steam, in Cents
Mean Pressure of Transmission 20 lbs. per sq. in. Absolute, T_s=228° F.						
3	330.1	0.1946	15.5	0.2235	960	0.535c
4	424.2	0.1746	32.5			0.295
5	523.8	0.1671	60.0			0.1888
6	623.9	0.1625	97.0			0.1352
8	812.5	0.1459	195.0			0.0785
10	1014.1	0.1421	350.0			0.0535
12	1203.0	0.1230	550.0			0.0352
Mean Pressure of Transmission 50 lbs. per sq. in., Absolute, T_s=281°F.						
3	488.8	0.1790		0 343	923.5	0.495c
4	627 9	0.1601				0.271
5	775.5	0.1542				0.175
6	923.7	0.1499				0.125
8	1203.0	0.1340				0.0725
10	1501.5	0.1306				0.0445
12	1780.0	0.1125				0.032
Mean Pressure of Transmission 100 lbs. per sq. in. Absolute, T_s=327.8° F.						
3	676 3	0.1651		0.476	880.0	0.4735c
4	868.8	0.1478				0.2590
5	1073.0	0.1416				0.1658
6	1278.0	0.1379				0.1210
8	1664.5	0.1234				0.0693
10	2077.5	0 1204				0.0468
12	2465.0	0 1037				0.0304

(Continued on next page)

The values of "E" used above are the commonly accepted values of Magnesia covering.

TABLE IV. (Cont'd.)

Pipe Size	$(T_s—T_a)C'$	(1—E) *	K'	$\sqrt{w}$	L'	Loss per 1000 lbs. Steam, in Cents
Mean Pressure of Transmission 200 lbs per sq. in. Absolute, T_s=381.9° F.						
3	896.8	0.1525		0.663	843.2	0.4380c
4	1152.1	0.1364				0.2410
5	1423.0	0.1306				0.1538
6	1694.9	0.1274				0.1108
8	2207.3	0.1140				0.0642
10	2275.0	0.1100				0.0430
12	3266.0	0.0954				0.0281

The losses, as given in Table IV, have been plotted against the nominal diameter of the pipe, as shown in Figure 2.

Combining the values of fixed charges from Table III, with the losses from Table IV, gives the total charges, per 1000 pounds of steam delivered, for a pipe line 100 feet long. These values are shown in Table V and are the basis for the plotting of Figure 3.

TABLE V

Total Delivery Charges per 1000 Pounds of Steam Delivered through A Pipe Line 100 Feet Long

Pipe Size	Fixed Charges	Losses	Total Delivery Charges
Mean Pressure of Transmission 20 lbs. per sq. in., Absolute.			
3	0.126c	0.535c	0.661c
4	.086	.295	.381
5	.063	.1888	.2581
6	.050	.1352	.1852
8	.0328	.0785	.1113
10	.0234	.0535	.0769
12	.0190	.0352	.0542

(Continued on next page)

TABLE V (Cont'd.)

Pipe Size	Fixed Charges	Losses	Total Delivery Charges
Mean Pressure of Transmission 50 lbs. per sq. in., Absolute.			
3	0.082	0.495	0.5570
4	.0556	.271	.3266
5	.0411	.175	.2161
6	.0330	.125	.1580
8	.02135	.0725	.0938
10	.0152	.0445	.0597
12	.0125	.0320	.0445
Mean Pressure of Transmission 100 lbs. per sq. in., Absolute.			
3	0.059	0.4735	0.5325
4	.040	.2590	.2990
5	.0298	.1658	.1956
6	.0238	.1210	.1448
8	.0154	.0693	.0847
10	.0110	.0468	.0578
12	.0090	.0304	.0394
Mean Pressure of Transmission 200 lbs per sq. in., Absolute.			
3	0.0424	0.4380	0.4804
4	.0288	.2410	.2698
5	.0214	.1538	.1752
6	.0171	.1108	.1279
8	.0110	.0642	.0752
10	.00788	.0430	.0509
12	.00647	.0281	.0346

Figure 4 is a reproduction of a steam flow chart for the well known Babcock formula. This chart was designed by Dean H. V. Carpenter and was published in Power, Dec. 17, 1912. From this chart, the necessary size of pipe, for any case, may be determined when the mean pressure of transmission, the allowable drop in pressure, and the load in pounds of steam per minute are known.

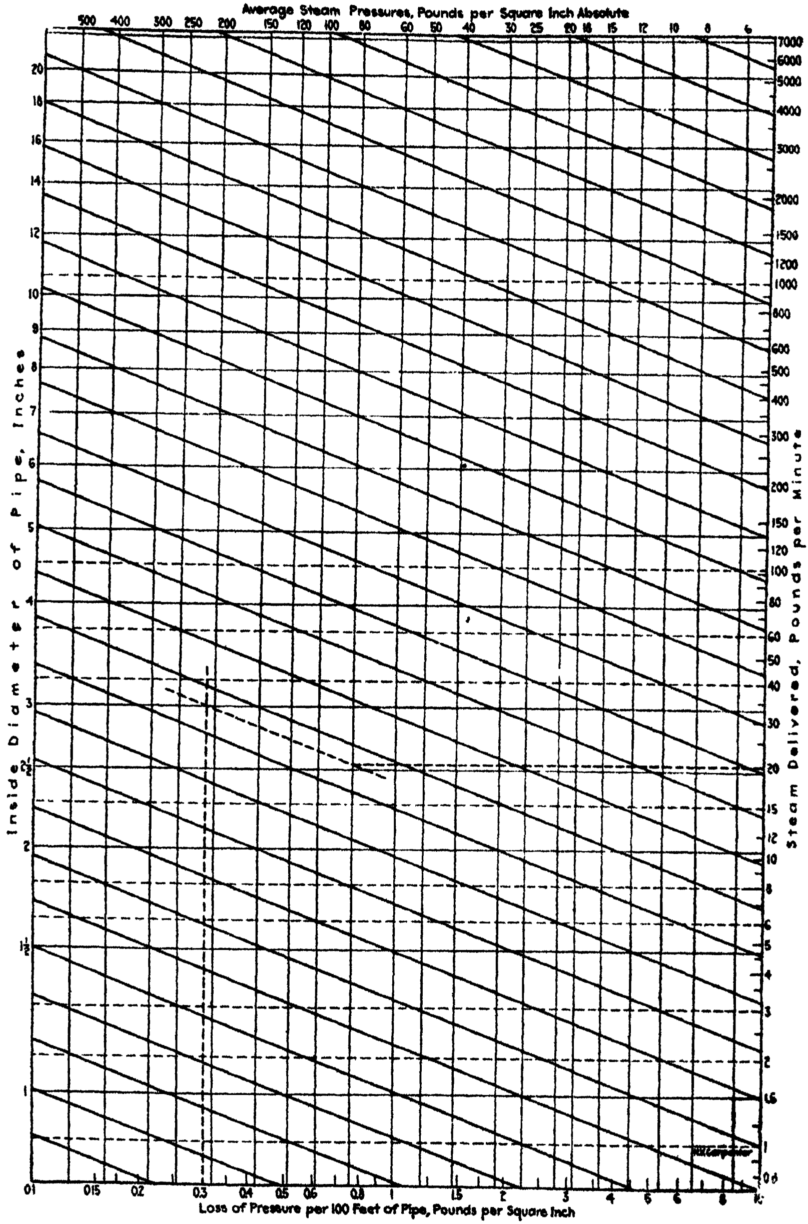

Average Steam Pressures, Pounds per Square Inch Absolute
500 400 300 250 200 150 120 100 80 60 50 40 30 25 20 18 15 12 10 8 6
Inside Diameter of Pipe, Inches
20 18 16 14 12 10 9 8 7 6 5 4 3 2½ 2 1½ 1
Steam Delivered, Pounds per Minute
7000 6000 5000 4000 3000 2000 1500 1200 1000 800 600 500 400 300 200 150 120 100 80 60 50 40 30 20 15 12 10 8 6 5 4 3 2 1.6 1 0.8
Loss of Pressure per 100 Feet of Pipe, Pounds per Square Inch
.01 .015 .02 .03 .04 .05 .06 .08 .1 .15 .2 .3 .4 .5 .6 .8 1

Figure 4

USE OF CHARTS

In order to illustrate the use of the charts, assume that it is desired to determine the relative costs of transmitting steam under the following conditions:

(1) Steam to be transmitted at 20 pounds per square inch, mean pressure.

(2) Steam to be transmitted at 100 pounds per square inch, mean pressure.

Assume that the maximum load on the line is to be 500 pounds of steam per minute and that a terminal pressure of 17 pounds per square inch absolute is required. The line to be 2000 feet in length.

Solution: Case (1)

The pressure at the mid-point of the line will be the mean pressure, or twenty (20) pounds, giving an allowable pressure drop, per 100 feet of line, (20—17)/10=0.3 lbs.

The size of the pipe, from Figure 4., to deliver 500 pounds of steam per minute, with the pressure drop of 0.3 lbs per 100 feet, is found to be 12-inch

The delivery charges, per 1000 pounds of steam, for 100 feet of pipe line are determined from Figure 3. Enter the chart at the 12-inch pipe size, on lower horizontal scale, pass vertically upward to the 20 pounds per square inch mean pressure line and then horizontally to the right hand scale. The total delivery charges are 0.0545 cents per 1000 pounds of steam delivered, on the basis of 1 pound pressure drop per 100 feet of pipe. This must now be corrected to the basis of 0.3 lbs pressure drop per 100 feet of line.

To obtain the "Correction Factor," enter the chart, Figure 3., at the 0.3 point on the scale of pressure drops, pass vertically upward to the pressure drop correction curve, thence horizontally to the left hand scale. The correction factor is 1.83.

The total delivery charges for this case are.

Total Delivery Charges = 1.83 × 0.0545

= 0.0995 cents per 1000 pounds of steam delivered, at 20 lbs. mean pressure, per 100 feet of pipe line.

Solution: Case 2.

There are two possible conditions of transmission under this case which need to be considered.

(1) The steam may be transmitted under a mean pressure of 100 pounds per square inch, allowing the same pressure drop per 100 feet as in Case 1, and then use a throttle valve at the delivery end to obtain the required 17 pounds pressure.

(2) Advantage may be taken of the higher pressure to obtain a greater pressure drop per 100 feet, thus using up the pressure in friction, and so obtaining the desired 17 pounds pressure at the delivery end.

Considering the first of these conditions, from Figure 4, it will be found that a 10-inch line will be required to transmit 500 pounds of steam per minute at a mean pressure of 100 pounds per square inch, with a pressure drop of 0.3 pounds per 100 feet.

From Figure 3, the delivery charges will be 0.057 cents per 1000 pounds of steam delivered, per 100 feet of line, for a pressure drop of 1 pound per 100 feet of line. The correction factor will be the same as in Case 1, namely, 1.83, so that,

The total delivery charges = 1.83 × 0.057
= 0.1042 cents per 1000 pounds of steam delivered, at 100 lbs. mean pressure, per 100 feet of pipe line.

When the second condition obtains the possible pressure drop will be $(100 - 17)/10 = 8.3$ lbs. per 100 feet of pipe line.

From Figure 4, a 5-inch line is indicated.

From Figure 3, the delivery charges are 0.195 cents per 1000 pounds of steam delivered, per 100 feet of line, for a pressure drop of 1 lb. per 100 feet. The correction factor is 0.345. Then, the total delivery charges for a pressure drop of 8.3 lbs. per 100 feet of pipe line, will be

The total delivery charges = 0.345 × 0.195
= 0.0672 cents per 1000 pounds steam delivered, per 100 feet of pipe line, at 100 lbs. mean pressure, and 8.3 lbs. pressure drop.

Delivery Charge, Load Factor less than 100 Percent

For a load factor other than 100 percent, there are three conditions under which the delivery charges need to be considered, namely,

(1) The line in operation 100 per cent of the time but carrying less than maximum load.

(2) The line in operation less than 100 percent of the time but carrying the maximum load while in operation.

(3) The line in operation less than 100 percent of the time and carrying less than the maximum load while in operation.

The first two of these, only, will be considered here.

As an example consider the 12-inch and the 5-inch lines of the previous problem to be operating at 50 percent load factor, other conditions as before.

Solution: Condition (1)

The steam flow in this case will be one-half of the maximum, or 250 pounds per minute. The yearly fixed charges will be the same as for the 100 percent load factor. The losses, due to the different mean pressure of transmission, will be somewhat different than those for 100 percent load factor. However, this difference will be negligible*, so that the delivery charges per 1000 pounds of steam delivered will be double those for 100 percent load factor.

Delivery charges, 12-inch line $= 2 \times 0.0995$
$= 0.199$ cents, per 1000 pounds of steam delivered, per 100 feet of pipe line.

Delivery charges, 5-inch line $= 2 \times 0.0672$
$= 0.1344$ cents per 1000 pounds of steam delivered, per 100 feet of pipe line.

Solution: Condition (2)

The average flow for this case will be 500 pounds per minute. The fixed charges, per 1000 pounds of steam delivered, will be double those for the case of 100 percent load factor, while the losses, per 1000 pounds

* See appendix, page 19.

of steam delivered, will be the same as in the case of 100 percent load factor.

For the 12-inch line, from Figure 1, the fixed charges are 0.019 cents, per 1000 pounds of steam delivered, per 100 feet of pipe line, for 1 pound pressure drop per 100 feet of line. The correction factor is the same as before, namely, 1.83.

Fixed Charges (100% L. F.) = 1.83 × 0.019
= 0.03477 cents per 1000 pounds of steam delivered, per 100 feet of pipe line, for a pressure drop of 0.3 pounds per 100 feet of line.

The losses, from Figure 2, are 0.0354 cents per 1000 pounds of steam delivered, per 100 feet of line, for a 1 pound pressure drop. The losses for a 0.3 pound pressure drop are, then

Losses (100% L. F.) = 1.83 × 0.0354
= 0.06478 cents per 1000 pounds of steam delivered, per 100 feet of line, for a pressure drop of 0.3 pounds per 100 feet.

The fixed charges, per 1000 pounds of steam delivered, for a 50 percent load factor will be,

Fixed Charges (50% L. F.) = 2 × 0.03477
= 0.06954 cents per 1000 pounds of steam delivered per 100 feet of line.

The losses, per 1000 pounds of steam delivered, for a 50 percent load factor will be the same as for the 100 percent load factor.

Losses (50% L. F.) = 0.06478 cents per 1000 pounds of steam delivered, per 100 feet of line.

The total delivery charges will then be,

Delivery Charges = Fixed Charges + Losses
= 0.06954 + 0.06478
= 0.13432 cents per 1000 pounds of steam delivered, per 100 feet of line, at 20 lbs. mean pressure and 50 per cent load factor.

For the 5-inch line, from Figure 1, the fixed charges are 0.0295 cents, per thousand pounds of steam delivered, per 100 feet of pipe line, for a

pressure drop of 1 pound per 100 feet of line. The correction factor is the same as in the previous problem, or 0.345.

Fixed Charges (100% L. F.) = 0.345 × 0.0295
= 0.010177 cents per 1000 pounds of steam delivered, per 100 feet of pipe line, for a pressure drop of 8.3 pounds per 100 feet of line.

The losses, from Figure 2, are 0.168 cents per 1000 pounds of steam delivered, per 100 feet of pipe line, for a 1 pound pressure drop per 100 feet of line. The losses for a 8.3 pounds pressure drop are, then:

Losses (100% L. F.) = 0.345 × 0.168
= 0.05796 cents per 1000 pounds of steam delivered, per 100 feet of line, for a pressure drop of 8.3 pounds per 100 feet of line.

The fixed charges, per 1000 pounds of steam delivered, for a 50 percent load factor, will be

Fixed Charges (50% L. F.) = 2 × 0.010177
= 0.020354 cents per 1000 pounds of steam delivered, per 100 feet of line.

The losses, per 1000 pounds of steam delivered, for a 50 percent load factor, will be the same as for a 100 percent load factor, namely

Losses (50% L. F.) = 0.05796 cents per 1000 pounds of steam delivered per 100 feet of line.

The total delivery charges will then be,

Delivery Charges (50% L. F.) = Fixed Charges + Losses.
= 0.020354 + 0.05796
= 0.07831 cents per 1000 pounds of steam delivered, per 100 feet of line, at 100 pounds mean pressure and 50 per cent load factor.

TABLE VI

Mean Pressure of Transmission lbs. sq. in. Absolute	Load Factor	Pressure Drop in Pounds, per 100 Feet of Line	Pipe Size Required	Delivery Charges per 1000 lbs. of Steam Delivered per 100 feet of Pipe Line.		
				Fixed Charges	Losses	Total Charges
20 lb.	100%	0.3 lb.	12"	0.03477c	0.06478c	0.09955c
100 lb.	100%	0.3 lb.	10"	0.020496c	0.08052c	0.101016c
100 lb.	100%	8.3 lb.	5"	0.010177c	0.05796c	0.068137c
20 lb.	50%*	0.3 lb.	12"	0.06954c	0.06478c	0.13432c
100 lb.	50%*	8.3 lb.	5"	0.020354c	0.05796c	0.078314c

CONCLUSION.

From the above examples, the results of which are tabulated in Table VI, it is seen that the transmitting of steam at high pressures, when the pressure drop per one hundred feet is the same as for the low pressure line, is more costly than the use of low pressures This is due to the fact that the greater heat loss from the high pressure line more than offsets the somewhat lower cost of the line. If, however, the greater pressure is used up in overcoming friction in a smaller line there is a saving, in the case of the example above, of approximately 50% in transmission charges for conditions of 100% load factor. The saving is even greater when the load factor is less than 100%; for example, the total charges for the 5-inch line operating at a 50% load factor are 0.07831 cents per 1000 pounds of steam delivered, while for the 12-inch line the charges are 0.13432 cents per 1000 pounds of steam delivered. This is a saving of .05601 cents per 1000 pounds of steam delivered or .05601/.13432 or 41.6% in favor of the high pressure transmission, even under conditions of 50% load factor.

Extreme accuracy is not claimed for the diagrams, but it is hoped that they may be of service in shortening the labor of determining the relative costs of transmission of steam under various conditions of service.

* Line in use less than 100 percent of the time but carrying maximum load while in operation.

APPENDIX

In problem 1, for the 5-inch line, the initial pressure would be $100 + 8.3 \times 10 = 183$ pounds per square inch absolute.

The pressure drop in this line will vary with the square of the weight of steam flowing (w^2) and inversely with the density (d).

As an approximation assume it to vary with w^2, the mean density not changing. Then when this 5-inch line is carrying 250 pounds per minute, the pressure drop will be:

$$\text{Pressure drop} = 8.3 \times (250/500)^2$$
$$= 2.075 \text{ pounds per 100 feet of line.}$$

The initial pressure remaining the same, the mean pressure of transmission will be:

$$\text{Mean pressure} = 183 - 2.075 \times 10$$
$$= 162.25 \text{ pounds per square inch absolute.}$$

From Figure 4, for a 5-inch line carrying 250 pounds, and a mean pressure of 162 pounds, the pressure drop is 1.5 pounds per 100 feet of line.

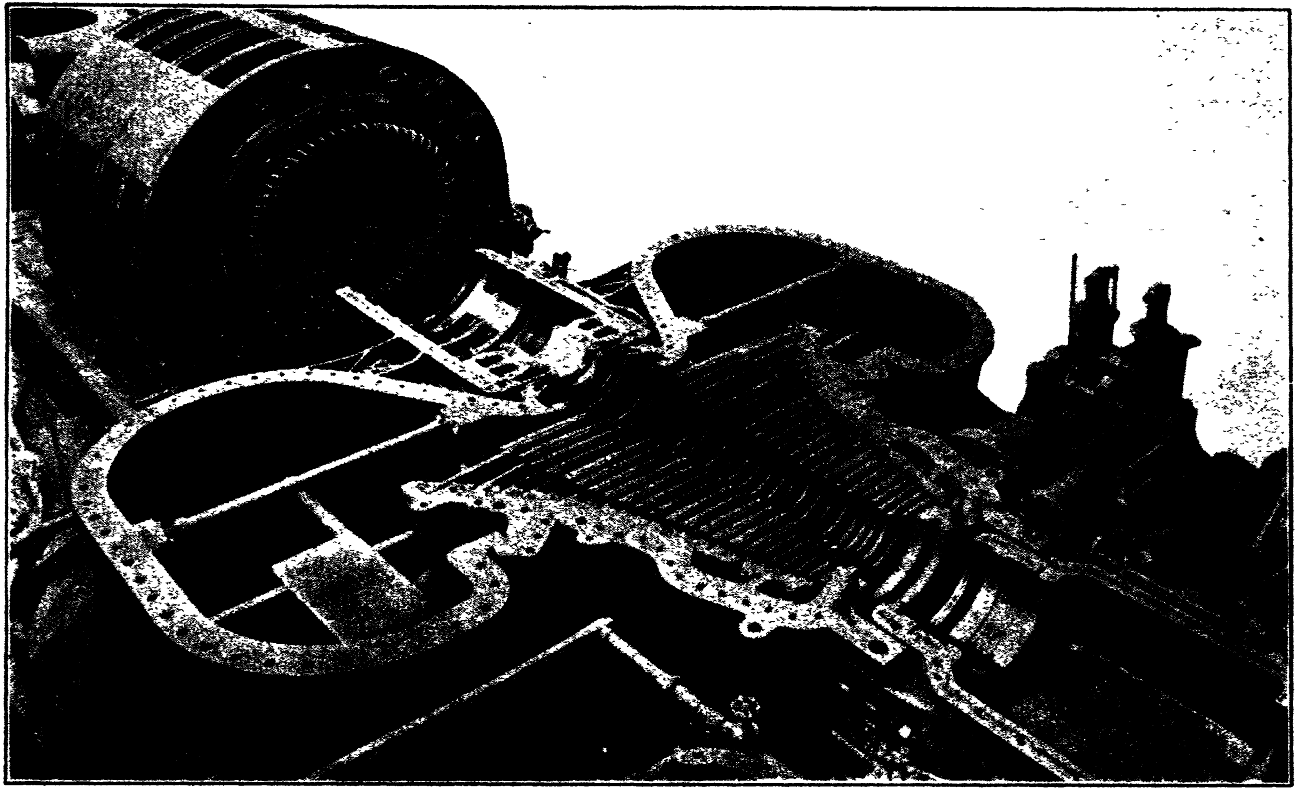
As a second approximation assume the pressure drop to be 1.5 pounds per 100 feet, then

$$\text{Mean pressure} = 183 - 1.5 \times 10$$
$$= 168 \text{ pounds per square inch absolute.}$$

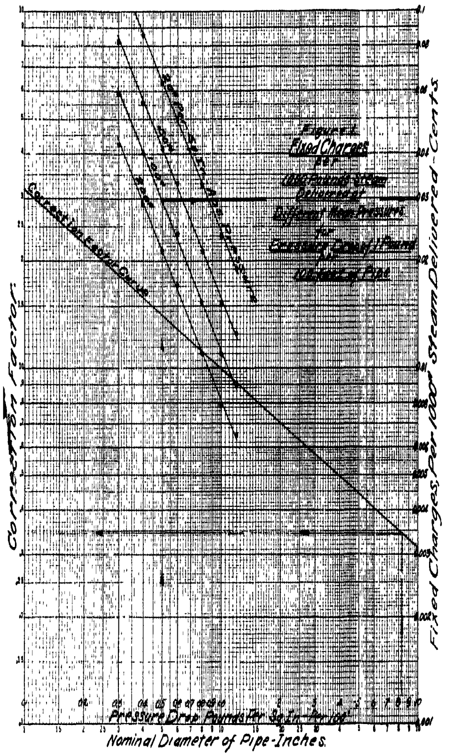
Again, from Figure 4, for a 5-inch line carrying 250 pounds of steam per minute, and a mean pressure of 168 pounds, the pressure drop is 1.45 pounds per 100 feet of line. This is sufficiently close to the approximation that the mean pressure may be taken as approximately equal to 170 pounds per square inch absolute.

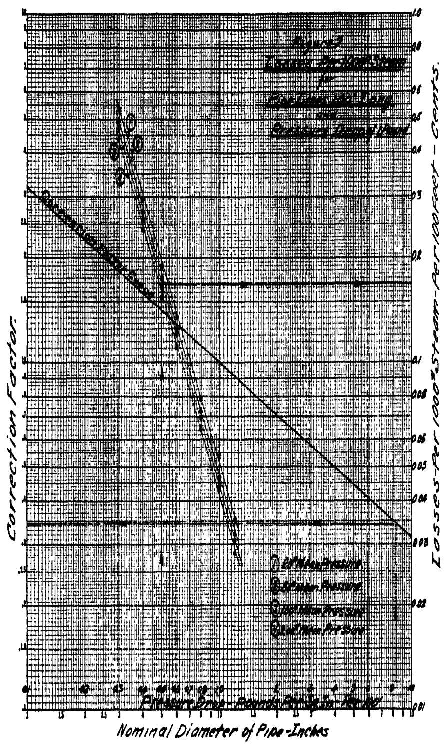
From Figure 2 the losses for a 5-inch line at a mean pressure of 170 pounds per square inch absolute are 0.164 cents per 100 pounds of steam delivered per 100 feet of line.

From the same diagram the losses for a 5-inch line at a mean pressure of 100 pounds per square inch are 0.17 cents per 1000 pounds of steam delivered. This is a difference in losses of $0.17 - 0.164 = 0.006$ cents per 1000 pounds of steam delivered, or an error of 0.6 of 1% in assuming no change in losses at 50% load factor.



Lower half of casing of large steam turbine


Fixed Charges
per
Fixed Charges, Per 1000# Steam Delivered - Cents.
Correction Factor.
Correction Factor Curve
Pressure Drop Pounds Per Sq. In. - Per 100'
Nominal Diameter of Pipe-Inches.


Losses-Per 1000# Steam-Per 100 Feet - Cents.
Correction Factor.
Correction Factor Curve
Pressure Drop - Pounds Per Sq. In. - Per 100'
Nominal Diameter of Pipe-Inches

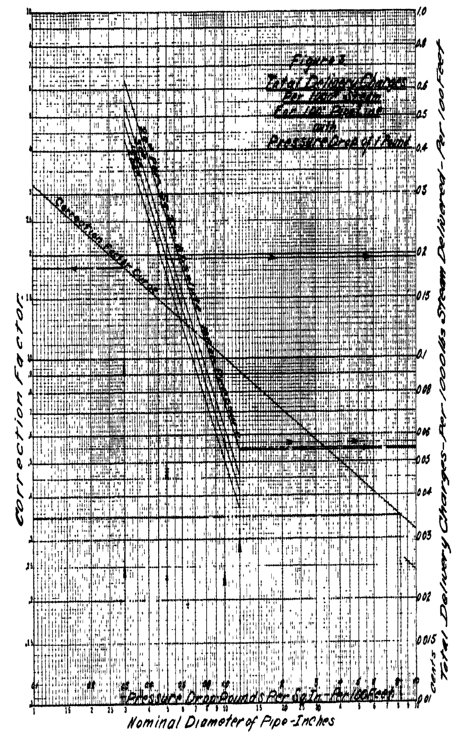


Figure 3
Total Delivery Charges
with
Pressure Drop of 1 Pound
Total Delivery Charges - Per 1000 lbs Steam Delivered - Per 100 Feet
Cents
Correction Factor.
Correction Factor Curve
Pressure Drop Pounds Per Sq. In. - Per 100 Feet
Nominal Diameter of Pipe-Inches

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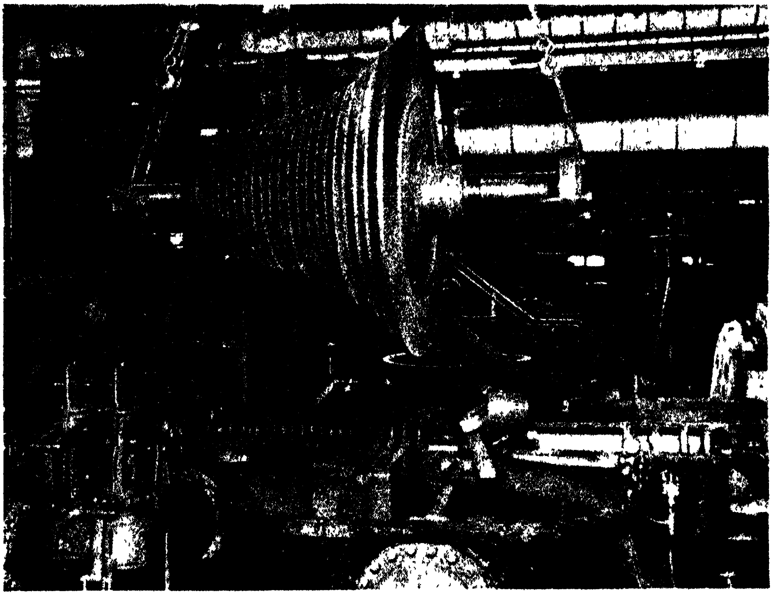

Installing the runner in a large steam turbine. Exhaust steam from such turbines is often used for district, or institutional heating.

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Vol. 12 | September, 1929 | No. 4

FIRST PROGRESS REPORT

Application of Stellite to Agricultural Tools

by

G. E. Thornton and C. C. Johnson

March, 1930

ENGINEERING BULLETIN NO. 33
ENGINEERING EXPERIMENT STATION
and
AGRICULTURAL EXPERIMENT STATION
cooperating

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

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APPLICATION OF STELLITE TO AGRICULTURAL TOOLS

By G. E. Thornton and C. C. Johnson *

INTRODUCTION

Plowing in the Palouse Country in dry seasons has been hampered to a great extent by the excessive wearing away of the plow shares. This excessive wear necessitates the sharpening of the shares at the end of a run of from four to eight hours duration

In looking for a remedy for this condition it was decided to try the application of Stellite to the cutting edge of the share and in this way increase its cutting life

Stellite is a very hard alloy which can be fused to other metal without affecting the characteristics of the Stellite. It is a ternary alloy of chromium, cobalt, and tungsten The No. 1 grade is usually used for Stelliting plow shares. After being applied the Stellite forms a thin, hard edge on the share which resists the abrasive action of the hard, dry soil.

These experiments were made in order to determine if the application of Stellite would really be profitable when applied to the cutting edge of farm tools such as plow shares, cultivator shovels, harrow teeth, disc blades, etc. For this purpose, comparison has

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* The authors are greatly indebted for assistance and suggestions as given by Mr. George Lommasson, Instructor in Welding at the State College who applied the Stellite, and by Mr. E. E. King, Mr. Gordon Klemgard, and Mr. Roy Wiggins, all farmers in the Palouse country who aided in carrying out these experiments.

NOTE: This experiment is to be continued during the summer fallow season of 1930. Definite figures will be determined for economy, resulting from saving of time on share changing, wear, sharpening, and from the saving reflected in the amount of gas and oil used in the tractor due to less draw bar pull required for the Stellited share over that required for the share which has not been Stellited and after it has worn blunt.

The results obtained from the Stelliting of harrow teeth and from Stelliting cultivator shovels will also be determined in this further study.

Figure 1
Rig No 1 One four-bottom and one five-bottom fourteen-inch John Deere Gang

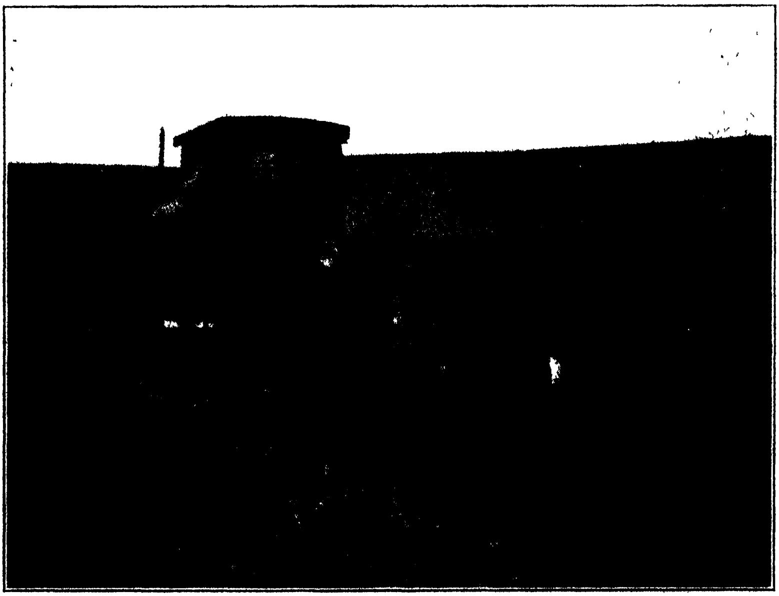

Figure 2
Rig No. 2. Four-bottom, sixteen-inch Oliver Gang.

been made, in two ways, of the life of treated and untreated tools. First, a graphic outline of the edge of a plow share was made before and after using. This was done with treated and untreated shares working in the same gang plow. Second, the wear was measured by determining accurately the loss of weight in each plow share due to wearing away of the metal.

The actual economy resulting from treating shares is determined by the saving in cost of sharpening, time lost due to share changes, trips to the shop for sharpening, etc. Considerable saving in gas when tractors are used has also been noticed.

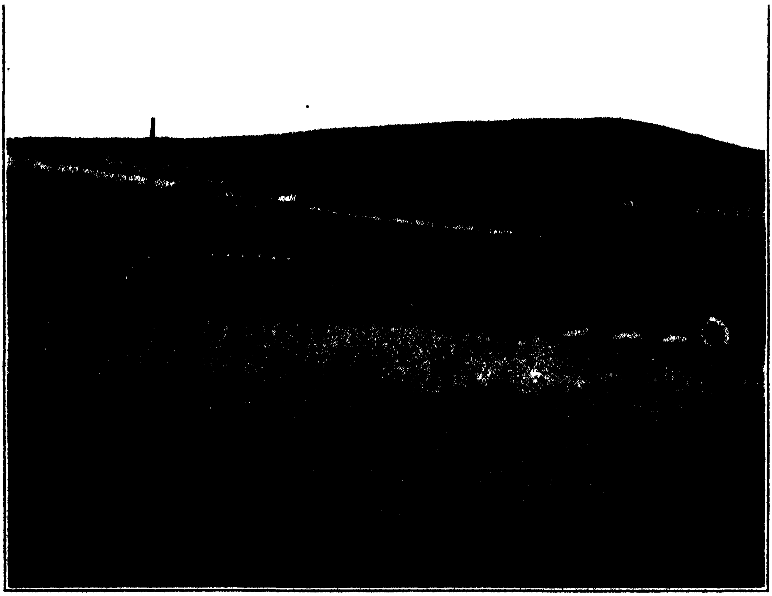

Figure 3
Rig No. 3. Five-bottom, fourteen-inch John Deere Gang

METHOD

The method of carrying on this experiment was to equip the same plowing rigs already in the field with both the treated and untreated shares. Treated shares are the ones to which the Stellite has been applied while the untreated shares are those which have not been Stellited and which were sharpened according to present custom.

Three plowing rigs pulled with tractors were used in these experiments, one five-bottom, fourteen inch John Deere, one four-bottom, fourteen-inch John Deere, and one four-bottom, sixteen-inch Oliver. The five-bottom John Deere was equipped with five-Stellited shares while the four-bottom plows were each equipped with two Stellited shares and two shares not Stellited.

Each share on the plow used traveled the same distance and plowed the same amount of ground. When the untreated shares were removed for sharpening the treated shares were also removed so that the amount of ground plowed would be the same.

The ground in which the experiments were performed was stubble land which had been in crop this last season. This land was dry and in many spots hard so that conditions were those usually found in the Palouse country in a very dry season.

The acreage plowed by each rig was measured by means of a revolution counter attached to the land wheel of the plow. Knowing the diameter of the wheel and the revolutions made by the wheel in the test the distance traveled by the plow could be determined. This distance multiplied by the cut of the plow gave the amount of land plowed.

This arrangement worked very successfully since the ground was dry and there was practically no slip to the land wheel. The counter was mounted within the wheel and protected from dirt and stubble so that its action was positive and accurate.

The results of this experiment may be shown in two ways: first, by the graphic outline method; and second, by an economic analysis showing the saving of money to the farmer.

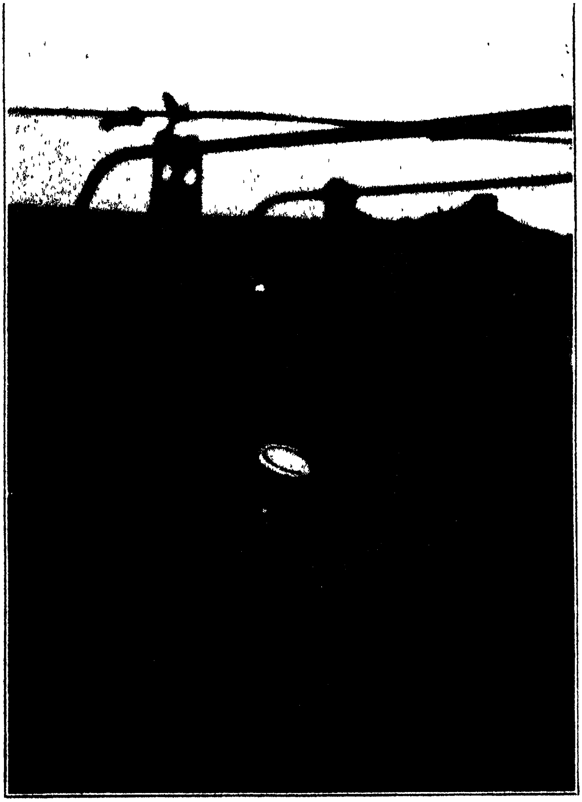

Figure 4
Revolution counter, with cover removed, on land wheel.
Note: Picture taken after rainy season had begun.

In the graphic method the outline of the shares was taken on paper for each group of shares. Group No. 1, consisting of four John Deere steel shares, is shown in Figure 5. No. 1 and No.2 of this group were treated with Stellite and No. 3 and No. 4 were used as received from the manufacturer. The full line outline indicates the share before the test was begun. The dashed line outline indicates the same after the test had been completed. This test was a run of twenty-seven hours in stubble land which included a number of hard

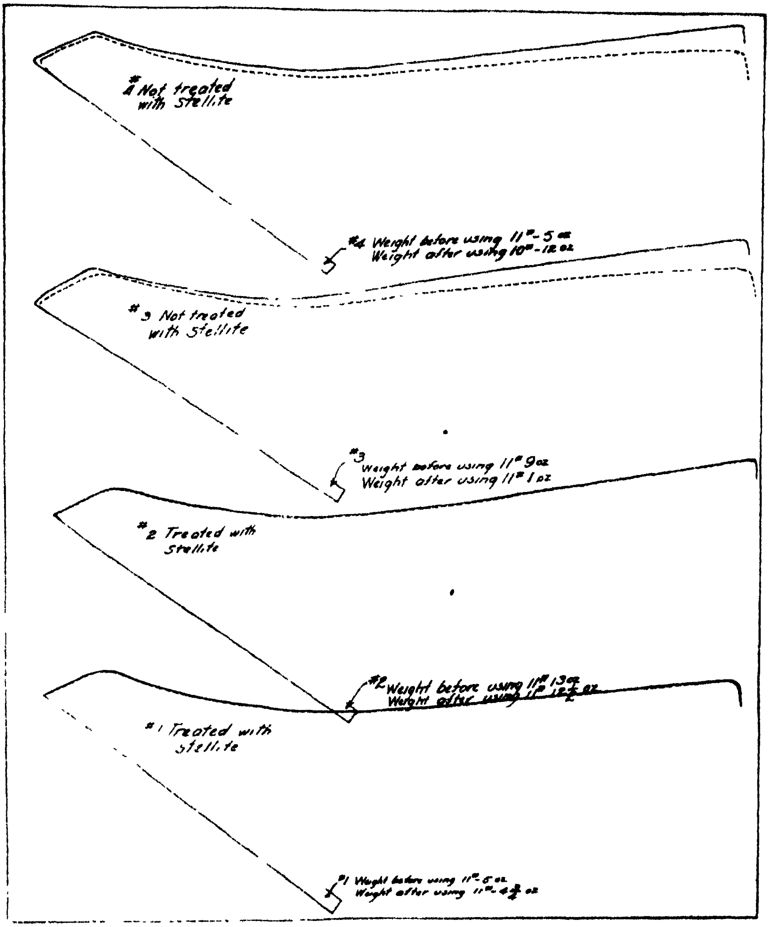

Figure 5
Outline drawing of four fourteen-inch John Deere shares before and after plowing 27 hours. Photograph was made of the full size drawing.

dry clay hill tops. The order of placing the shares on the plow was as follows: No. 1 at the front end of the plow, then No. 3, No. 2, and No. 4.

The metal worn away on the shares was barely noticeable on No. 1 and No. 2, but No. 3 lost eight ounces and No. 4 lost nine ounces of metal in the twenty-seven hour run.

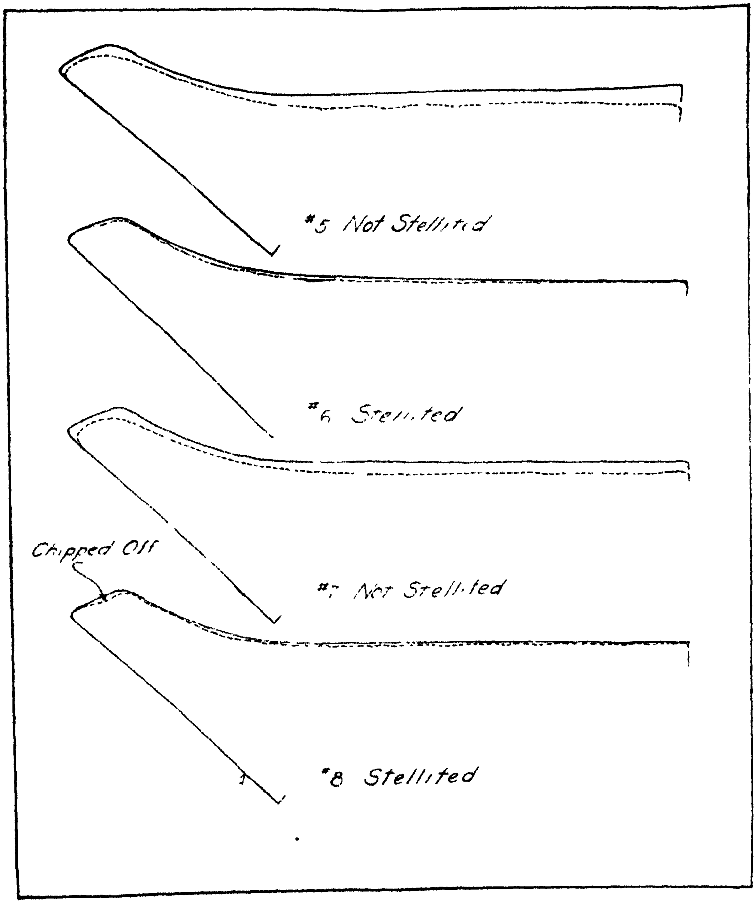

Figure 6

Outline drawing of four sixteen-inch Oliver Shares before and after plowing 80 acres of stubble land.

Figure 6 shows four Oliver sixteen-inch shares after completing a run of 59½ hours. In this time the plow had turned over 80 acres or an average of 20 acres per share. The ground in which this plow operated was dry stubble land. Shares No. 6 and No. 8 were given an application of Stellite while No. 5 and No. 7 were untreated.

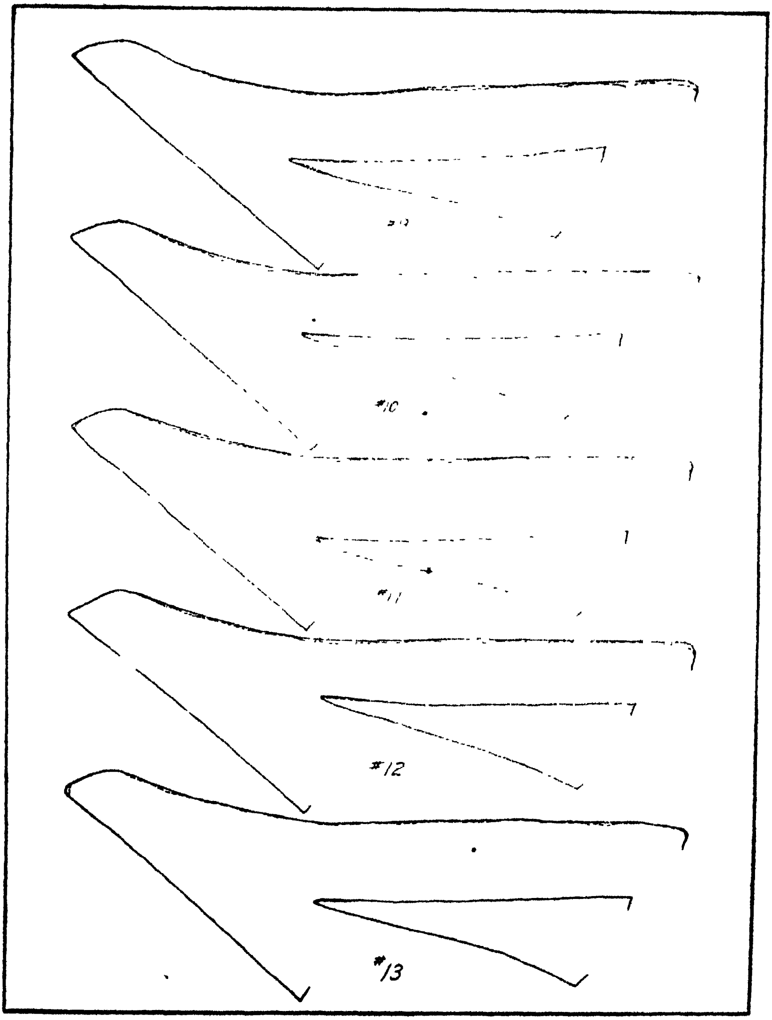

Figure 7

Outline drawing of five fourteen-inch John Deere shares before and after plowing 100 acres of stubble land.

No. 5 and No. 7 were removed for sharpening after the rig had plowed 28 acres, or 19 hours, and were again put in service with the Stellited shares.

The metal worn away on this test was not determined because of the effect of sharpening shares No. 5 and No 7.

Figure 7 shows five fourteen-inch John Deere shares, all of which had been treated with Stellite. Before the Stellite was applied, the edge of the share was drawn out and the point drawn out and knocked down so as to present a thinner cutting edge to the ground during the plowing operation. As before, the full line outline represents the share before commencing plowing and the dashed line outline after the test had been completed. The way in which the point of the plow is protected by the Stellite is shown in Figure 7.

DATA

Rig No. 1. One four-bottom fourteen-inch John Deere Gang.

Steel Shares

Share No.	Treatment	Remarks
1.	Stellited	Lost less than one-half ounce.
2.	Stellited	Lost less than one-half ounce.
3.	Not Stellited	Lost nine ounces.
4.	Not Stellited	Lost eight ounces.

Total acreage plowed 50 acres.

Duration of run 27 hours.

Note: All shares were removed as soon as shares No. 3 and No. 4 required sharpening so that a comparison could be made of the amount of metal worn away.

Rig No. 2. One Five-bottom fourteen-inch John Deere Gang.

Soft center shares

Share No	Treatment	Remarks
5.	Not Stellited	Removed for sharpening after 19 hours run.
6.	Stellited	Good cutting edge left after 80-acre plowing test.
7.	Not Stellited	Removed for sharpening after 19 hours run.
8.	Stellited	Point slightly chipped but remainder of edge good after 80-acre plowing test.

Total acreage plowed 80 acres.

Duration of run 59.5 hours.

Rig No. 3. One four-bottom sixteen-inch Oliver Gang.

Steel shares.

Share No.	Treatment	Remarks
9.	Stellited	Cutting edge on all shares in excellent condition after 100-acre plowing test.
10.	Stellited	
11.	Stellited	
12.	Stellited	
13.	Stellited	

Total acreage plowed 100 acres.

Duration of run—not determined

In arriving at the saving which resulted from the application of the Stellite several variables entered into the consideration which will make the final conclusion rather flexible. Each farmer puts a certain value on the operation of the plowing rig which he is using. If that rig is laid up for repairs or sharpening of shares the loss of time necessarily results in a different value depending on the value of the rig per day to the owner. From $2.50 to $3.00 is considered an average value per day.

The cost of sharpening shares was standard, varying from forty to sixty cents between a fourteen- and a sixteen-inch share

In reaching a final conclusion, the average cost of operation per hour for the tractor and the cost of sharpening must be taken into consideration. Average operations this season called for sharpening the shares at the end of every day's run.

Such things as saving of fuel and oil for the tractor were not determined, but it was noticeable that the tractive effort required for the dull share was in excess of that required for the Stellited share.

CONCLUSION

In conclusion it will be well to mention the views of several prominent farmers of this region who have used the Stellited shares in the fall plowing season of 1929.

Mr. Gordon Klemgard, Pullman, Washington, operator of Rig No. 1.

"Certainly is a wonderful help to the farmer in dry land plowing. I am certainly sold on the proposition."

Mr. E. E. King, Pullman, Washington, operator of Rig No. 2.

"Certainly saves time in share changes and results in a saving of gas and oil in the tractor. Would be interested in determining just what saving is made in gas and oil."

Mr. Roy Wiggins, Colton, Washington, operator of Rig. No. 3.

"So far have plowed 100 acres of tough land with one application of Stellite and the shares are still good for 100 or 200 acres more."

APPLICATION OF STELLITE

The technique involved in the application of the Stellite to the cutting tools is not complicated and can be performed after a little practice by any mechanic familiar with the operation of an oxy-acetylene torch.

In applying the Stellite, precautions should be used to prevent burning the thin edge of the plow share. The share should be heated for a short distance, from 1¼ to 1½ inches, back from the cutting edge as the application of Steelite proceeds from the heel toward the point. Heat back from the edge of the share first, and work out toward the cutting edge, interposing the Stellite rod between the flame of the torch and the cutting edge of the share as the edge is approached. This scatters the flame and prevents burning the edge. See Figure 8

Sufficient Stellite should be provided in a single rod so that the operation may be completed without allowing the share to cool off. If cooling is permitted the cutting edge is checked at the point where operations cease and after a short time a crack will develop perpendicular to the cutting edge at this point.

The amount of Stellite applied to each share varies from three to seven ounces for the fourteen-inch share. Better results are obtained with the unhardened steel share than with the hardened or soft centered shares. With the two types last mentioned the application of the Stellite is accompanied by warping unless the share is gripped along the back edge in a long jawed vise.

When the ground is dry and hard the Stellite should be applied to the under surface of the share. For spring plowing or plowing in

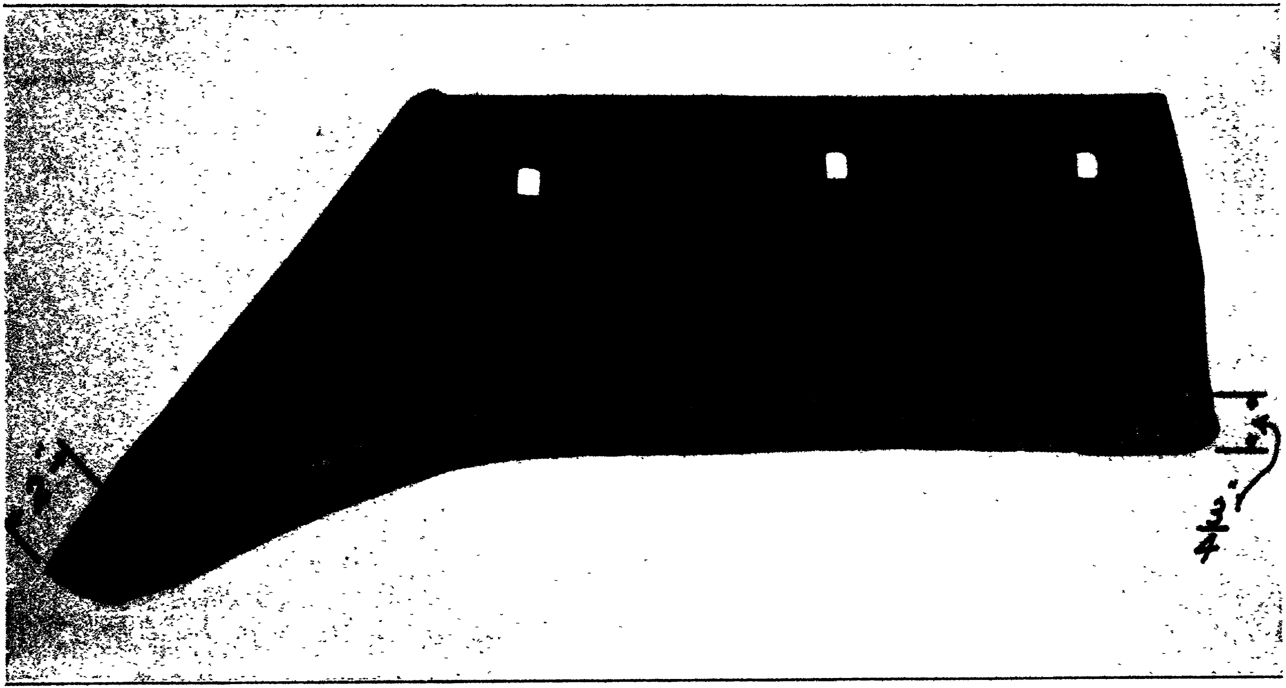

Figure 8
Bottom view of share after being Stellited

Figure 9
Applying Stellite to bottom surface of plow share

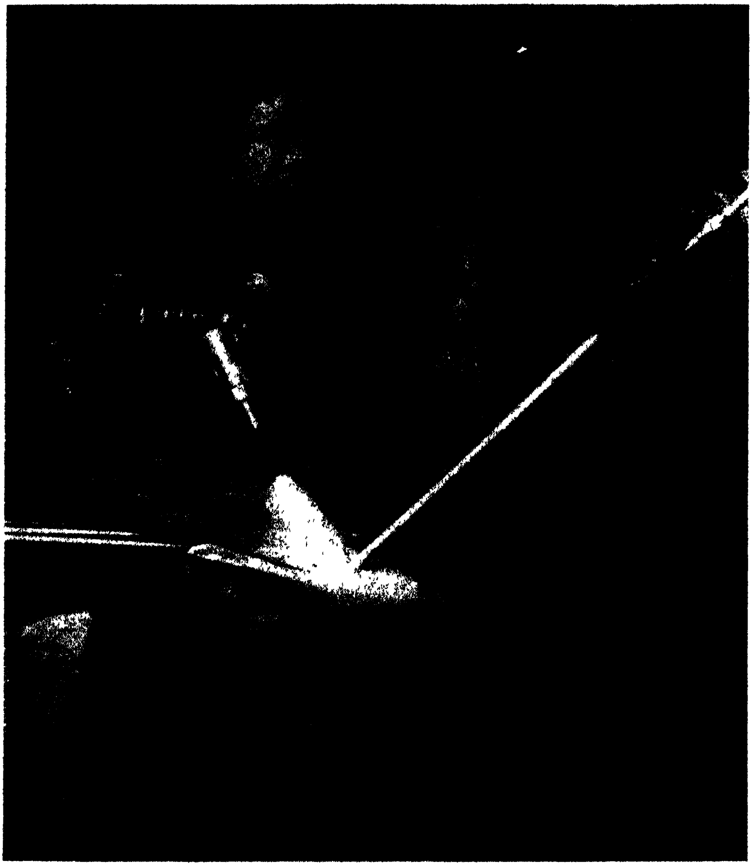

Figure 10

Applying Stellite to point of share and building it out over point with the aid of carbon blocks.

moist, mellow ground, it may be applied either on the top or the bottom surface along the cutting edge.

In most cases the share when new should be drawn out on the edge and the point knocked down before the Stellite is applied. The preparation of the point is of special importance in order to maintain the "suck" of the share into the ground. The Stellite should be applied to both the top and bottom surface of the point, and also on the land side for a distance of about two inches back from the point.

The Stellite should be built out over the point so as to present a complete Stellited cutting edge. This building out of the Stellite over the point may be accomplished by means of a carbon block to which the Stellite does not adhere. The point of the share is rested upon the block as shown in Figure 10. The point is heated and the Stellite worked down over the point with the Stellite rod. If scale appears on the surface of the metal it can be removed with a file which should be placed on the bench within easy reach.

Note:

Haynes Stellite, the special vise for holding the plow shares, and the carbon block can be obtained from the Haynes Stellite Company of Chicago or from the Linde-Oxweld Company of Seattle, Washington or elsewhere.

Engineering Bulletins

Published by the Engineering Experiment Station

State College of Washington

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By O. L. Waller and M. K. Snyder, March, 1914, July, 1916.
2. How to Measure Water.
By O. L. Waller, October, 1915, Reprint 1925 (Revised and Reprinted as part of Engineering Bulletin No. 20.)
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By M. K. Snyder. See Engineering Bul. No's 9, 10, and 11.
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By F. D. Heald, J. R. Neller and F.L Overeley of the Agricultural Experiment Station in Cooperation with H. J. Dana.

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By A. C. Abell, February, 1930.

33. Application of Stellite to Agricultural Tools. First Progress Report.
By G. E. Thornton and C. C. Johnson, September, 1929.

MONTHLY BULLETIN

OF THE STATE COLLEGE OF WASHINGTON

PULLMAN, WASHINGTON

Volume 12 April, 1930 No. 11

FIRST PROGRESS REPORT

THE LABORATORY DEVELOPMENT

OF AN

Electro-Hydrometallurgical Process for Copper Flotation Concentrate

Low Temperature Roasting
Purification by Neutral Leaching
Low-Acid Leaching. High-Acid Leaching.
Counter-Current Decantation and Filtration
Copper Electrodeposition

by

Arthur Eilert Drucker

and

Carl Frederick Floe

ENGINEERING BULLETIN NO. 35

ENGINEERING EXPERIMENT STATION

H. V. Carpenter, Director

Entered as second-class matter September 5, 1919, at the postoffice at Pullman, Wash., under Act of Aug. 24, 1912

The ENGINEERING EXPERIMENT STATION of the State College of Washington was established on the authority of the act passed by the first Legislature of the State of Washington, March 28, 1890, which established a "State Agricultural College and School of Science," and instructed its commission **"to further the application of the principles of physical science to industrial pursuits."** The spirit of this act has been followed out for many years by the Engineering Staff, which has carried on experimental investigations and published the results in the form of bulletins. The first adoption of a definite program in Engineering research, with an appropriation for its maintenance, was made by the Board of Regents, June 21st 1911. This was followed by later appropriations. In April, 1919, this department was officially designated, Engineering Experiment Station.

The scope of the Engineering Experiment Station covers research in engineering problems of general interest to the citizens of the State of Washington. The Work of the station is made available to the public through technical reports, popular bulletins, and public service. The last named includes tests and analyses of coal, tests and analyses of road materials, testing of commercial steam pipe coverings, calibration of electrical instruments, testing of strength of materials, efficiency studies in power plants, testing of hydraulic machinery, testing of small engines and motors, consultation with regard to theory and design of experimental apparatus, preliminary advice to inventors, etc.

Popular bulletins are available as listed on pages 42 and 43.

Requests for copies of the engineering bulletins an inquiries for information on engineering and industrial problems should be addressed to The Engineering Experiment Station, State College of Washington, Pullman, Washington.

The control of the Engineering Experiment Station is vested in the Board of Regents of the State College of Washington.

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THE LABORATORY DEVELOPMENT of an ELECTRO-HYDROMETALLURGICAL PROCESS for COPPER FLOTATION CONCENTRATE

By Arthur Eilert Drucker and Carl Frederick Floe

INTRODUCTION

The field of application of the hydrometallurgical processes for the recovery of metals from their ores has been rapidly expanded in the last few years. This has been partly due to the fact that the old methods of treatment could not be applied economically to the extraction of the metals from the more complex and lower grade ores, and partly to the increased knowledge of the chemical or wet processes. Great improvements in plant equipment have also aided materially in the advancement of this method of treatment.

Hydrometallurgical methods for the extraction of copper have been largely confined to the treatment of low grade oxidized ores. Some experiments have been conducted in an effort to apply these methods to the treatment of high grade copper sulphides, but in no case has it been used on a large commercial scale. In the Pacific Northwest, the abundance of cheap hydro-electric power offers every advantage for such a process as applied to simple suphide copper ores (mill concentrate), and makes the possibilities for such treatment well worth consideration and investigation at this time. Selective flotation methods have certainly paved the way. The purpose of this First Progress Report bulletin is to shew the results of some preliminary tests conducted in our own laboratories, and if possible to stimulate further research along this line.

Some metallurgists have agreed that a hydrometallurgical process for copper sulphides offers considerable possibilities, but only in a very few

cases have the results of actual tests been published. P. Middleton, in 1919, published results but these were not entirely complete and he urged that the investigations be continued, since the process showed considerable promise. Others may have made investigations, but we have been able to find but very few actual results. Certainly the small amount of material published and available on this particular phase of hydro-metallurgy well warrants that further tests be conducted.

William E. Greenawalt, a recognized authority on copper hydro-metallurgy, has the following to say about such a process for concentrate (Feb., 1930 "Mining Truth," Spokane, Washington):

"I want to state positively that there is no difficulty now, of any unusual sort, of producing electrolytic copper direct from the ore or concentrate. The concentrate is preferred for the reason that the roasting and leaching installation is greatly cheapened, both of installation and operation. Hundreds of careful roasting tests recently conducted prove conclusively that from 70 to 80 per cent of the copper can be made water soluble by careful roasting, and that a very high extraction of copper is obtainable by dilute acid leaching. The water soluble copper, on electrolysis to produce electrolytic copper, furnishes the acid, at no additional cost, to leach the copper from the ore which is not soluble in water. There is therefore, no acid expense in connection with the copper leaching and electrolysis.

"Careful tests, with a complete miniature plant, have proved that fully 1.4 pounds of copper can be deposited per kilowatt hour, with the simultaneous regeneration of all the acid required to leach the copper from the roasted ore or concentrate. The resulting electrolytic copper is as pure as that made anywhere.

"On roasting and leaching, a fairly high grade copper concentrate will shrink close to 50 per cent in weight, and if the concentrate contains precious metals, the residue of the concentrate leaching will assay about twice as much as the original concentrate, due to weight shrinkage. This copper leached concentrate residue can then be easily treated, as with cyanide, to recover the precious metals in their elemental form, and the metal so recovered could be sent direct to the mint, if the content is appreciable.

"There is no bigger and better prospective field now in mining than the electrolytic methods, especially for copper as applied to concentrate. Copper leaching and electrolysis should find a wider application than zinc leaching and electrolysis. About twice as much copper is deposited per kilowatt hour as zinc, and copper has more than twice the value of zinc.

"Any process that can be carried out on a small scale can be carried out on a large scale, if the same conditions are observed. The essential small-scale test work, as applied to electrolysis, is to carry it out cyclically, the same as in a large plant, so as to give the process a chance to develop any factors for or against the process. When this is done, there is positively no difference between a small-scale operation and a large-scale, or commercial, operation. At least, I have never found any difference. In leaching and electrolysis of copper solutions, if a minature plant is installed, to deposit, say a few pounds of copper per day, and operated cyclically, so that the operation will be complete in all its details, I will make the very positive statement that no new situation or conditions will arise in the operation of a larger plant. I believe, too, that this statement will be verified by every experienced metallurgist."

In general, the application of a hydro-metallurgical process to sulphide copper concentrates will involve three steps; roasting, leaching, and precipitation (electrolysis). The main problems to be worked out are:

1. The proper conditions of roasting in order that the insoluble copper sulphides may be converted into a form that is soluble in the dilute acid solvent.

2. Keeping down the impurities of the electrolyte (mainly iron) in order that a pure deposit of copper can be efficiently made.

3. Avoiding an accumulation of an excessive amount of acid, due to the formation of water soluble copper sulphate in the roast.

4. Proper conditions of electrolysis.

5. Removing gold and silver values from the tailing, if there is a sufficient amount present to make it pay.

Our experiments at the State College of Washington have been conducted on a small laboratory scale. The next step necessary is to con-

struct a small continuously operating laboratory plant in order to obtain results and operative conditions similar to those obtained in practice. After this a pilot-plant should be used treating several tons of concentrate per day, to check results, before erecting a large plant. Furthermore, the economics of the process should be given careful consideration. It must be clearly understood that a plant of commercial size, and there is an economical lower limit to this, with an ample source of ore supply to keep it running the year around, is necessary, as with all other similar operations. In many cases the conditions of freight rates, smelter schedules, and other considerations will determine whether or not an installation will pay.

Nothing new or original is claimed in any of the chemical reactions or principles involved. All have been known to chemistry for many years past. However the application (chemically, physically and mechanically) of these known principles and reactions, to the extraction of electrolytic copper from (mill) table and flotation sulphide concentrate is comparatively new, and has not been made on a full commerical scale, so far as we know now. Chas. R. Baroch describes in the E. & M. J., Nov. 30, 1929 tests on a semi-commercial scale at the Bagdad Copper Co., Hillside, Arizona. We have not been able to find complete published results for such a treatment of copper flotation mill concentrate. Conditions at the present time seem to be particularly favorable for research in this special field of metallurgy. Selective flotation methods have advanced to such an extent that this process need not be complicated with the cleaner and higher grade copper concentrate now available for treatment.

ORES TESTED

Two different types of ore were used in the tests: bornite from the Index Copper Company, Index, Washington, and chalcopyrite from the Royal Development Company, Leavenworth, Washington. Tests on the former were performed first, and were designed to show the effect of roasting at various temperatures on the solubility of the iron and copper. Later tests on the chalcopyrite ore were for the purpose of determining the proper strength of leach solution, and for the production of a comparatively pure electrolyte from which the copper could be economically precipitated by electrolysis.

ROASTING AND LEACHING TESTS ON INDEX COPPER ORE

Nature of the Ore:

The sample used in the roasting tests came from the mine of the Index Copper Company, Index, Washington. It consisted mainly of bornite coarsely disseminated in a gangue of country rock. Large crystals of chalcopyrite were also scattered through some pieces, and many were embedded in a ground mass of coarsely crystalline calcite. Crystals of finely disseminated pyrite were dispersed throughout the gangue, which consisted mainly of calcite, chlorite, quartz, and small amounts of feldspar.

A microscopic examination showed that the copper minerals were entirely liberated from the gangue when crushed to -48 mesh. Bornite crystals largely predominated, and it was estimated that 85% of the copper present was in this form. Considerable pyrite was also present.

Screen Analysis (Index Ore)

Mesh (Screen Ratio-Tyler $\sqrt{2}$)	—48 Mesh	—100 Mesh
+ 65	14.5%	0%
— 65 + 100	22.6%	0%
—100 + 150	14.2%	12.6%
—150 + 200	23.6%	28.5%
—200	25.1%	0%

Dusting losses were added to the undersize of the finest screen, as recommended by the Tyler Company.

Quantitative Analysis

Copper	20.72%
Iron	12.12%
Sulphur	23.12%
Gold	0.90 oz./T.
Silver	7.62 oz./T.
Other Soluble Bases	4.59%
Insolubles	39.45%

Equipment and Method:

Roasting was accomplished by means of a 13 Ampere, 110 volt Multiple Unit Electric Furnace, having a muffle 4½" × 13" in size. Sixty-

gram samples were roasted each time in two shallow roasting dishes. The furnace was connected in series with a brine solution rheostat, which permitted a close control of the temperature. Temperature was measured with a Stupakoff Platinum-Iridium thermo-couple, introduced through a small opening at the end of the muffle. The ore, after being weighed and placed in the roasting dishes, was introduced into the muffle and the current turned on. When the desired temperature was reached, the rheostat was adjusted, and the temperature kept as constant as possible The variation due to imperfect adjustment never exceeded 10 degrees An opening at each end of the muffle permitted a circulation of air, but it was necessary to remove the charge from the muffle every thirty minutes in order to rabble it.

The charge after roasting was leached with water and then with a 10% solution of sulphuric acid. Fifty grams of the roasted ore was agitated for three hours with 250 cc of the acid.

Electrolytic Deposition:

A Tungar Rectifier supplied the (direct) current for an electrolytic cell containing two copper sheet cathodes and three lead anodes each 2" × 3½" in size, which were spaced 2" apart. A slide wire rheostat permitted a variation in the current density Circulation of the electrolyte was maintained by two siphons.

Assays:

Because of the large amount of copper in the ore, the assays for gold and silver had to be a combination wet and fire method. Van Liews nitric acid method of leaching out the copper was used. The silver was precipitated by the addition of a salt solution. After leaching, the residue was assayed as described on pages 125-126 of Fulton's "Manual of Fire Assaying."

Copper was determined by the standard potassium iodide method, and iron by the permanganate method. An outline of procedure may be found in Low's "Notes on Technical Ore Analysis."

Results of Tests:

The curves plotted in Figures 2, 3, and 4, show very broadly the variation in the solubilities of iron and copper with the variation in the

roasting temperature. An examination of Fig. 2 reveals that the amount of water soluble copper sulphate formed reaches a maximum at approximately 650° C, and thereafter declines very rapidly. The total soluble copper (Fig. 3) reaches a maximum at about 625° C, and declines very rapidly after 650° C. This would seem to indicate that the sulphate in breaking down forms insoluble ferrites or silicates which rapidly decrease the percentage of extraction of the copper. Cupric oxide is also formed but this should be soluble in the dilute sulphuric acid.

Fig. 4 shows the amount of soluble iron formed at the various temperatures It is observed that within the limits tested, the amount of insoluble ferric oxide formed is nearly a straight line function of the temperature, with the exception of one break at about 650° C, when a retardation in the rate occurs. It is believed that the addition of more air to the roasting furnace would oxidize the iron at lower temperatures and thus render more of it insoluble.

Table I shows the results of roasting various samples of the raw ore, ground to -48 M and to -100 M, at temperatures ranging from 590° C. to 850° C. Table II shows the results of leaching the various roasted products with a 10% solution of sulphuric acid.

Tabulated Results of Tests

TABLE I

Roasting Tests

Temperature Degrees C.	Mesh	Hours of Roasting *	% S. after Roasting	% Cu. Soluble in Water
590	— 48	8	6.70	42.7
590	—100	8	6.61	43.3
650	— 48	8	6.07	44.7
650	—100	8	5.91	51.7
750	— 48	7	5.35	2.1
750	—100	7	4.39	2.4
850	— 48	6	3.70	0.0
850	—100	6	3.10	0.0

Intermittent hand-rabbling.

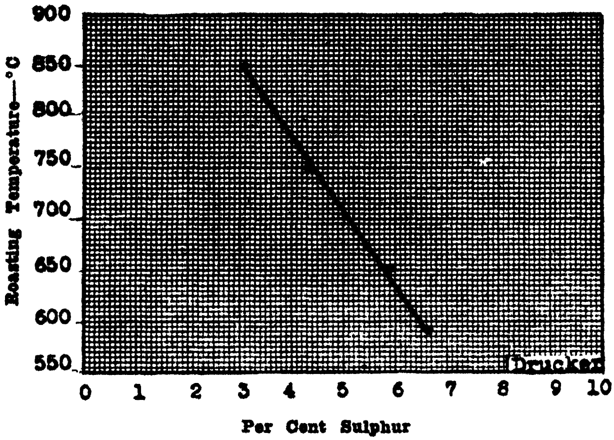


Figure 1. Curve showing amount of sulphur remaining in Index Copper Ore after roasting at various temperatures. (—100M)

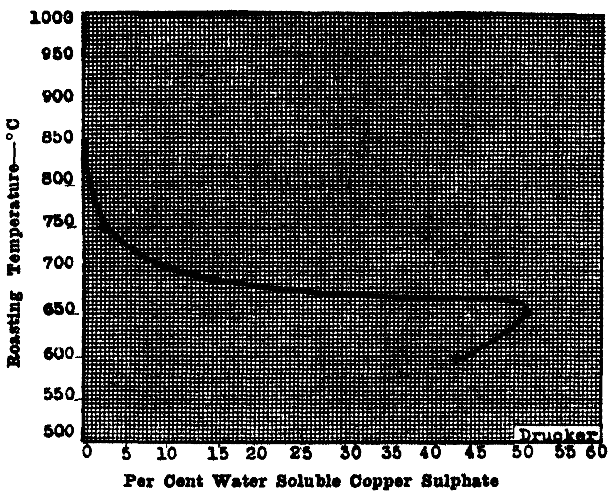


Figure 2. Broadly plotted curve, showing the amount of water soluble Copper Sulphate formed by roasting Index Copper Ore at various temperatures. (—100M)

TABLE II
Leaching Tests.

Mesh	Temp. of Roasting	% Total Fe. Sol. in 10% H_2SO_4	% Total Cu. Sol. in 10% H_2SO_4	Lbs. Cu. in Tails per Ton of Ore	Value of Cu. @ 18 (Tails)	Assay of Tails—oz.	
						Au.	Ag.
— 48	590	58.7	94.8	21.1	$3.81	1.23	11.7
—100	590	62.4	95.6	18.0	3.25	1.38	12.5
— 48	650	38.9	94.7	21.9	3.95	1.40	11.0
—100	650	40.6	92.3	31.9	5.74	1.24	11.2
— 48	750	18.3	32.8	278.5	50.13	1.16	7.9
—100	750	23.0	41.1	243.7	43.87	1.23	8.3
— 48	850	3.5	36.9	261.5	47.07	1.42	9.1
—100	850	7.6	46.9	220.0	39.60	1.18	9.3

Pounds (lbs.) of copper in heads per ton of ore equals 414.4.

Panning of the products from the -48 M roasts, showed that they still contained particles of undecomposed sulphides. This accounts for the lower extraction of this mesh sample. A longer roasting period would overcome much of the effect of coarser screen sizes. The results tabulated in the above mentioned tables indicate that the best roasting temperature lies somewhere between 590° C and 650° C. and that it is better to grind to -100 M in order to insure a complete decomposition of the sulphides. After determining this a new sample ground to -100 M was roasted for eight hours at 625° C with the following results:

TABLE III
Results of Roasting a —100 Mesh Sample at 625° C. for 8 hours.

(This sample is not a clean concentrate)

Sample	Per Cent Copper Soluble in Water — 47.34%					
	Wt. Gms.	Sulphur	Copper	Gold oz.	Silver oz	Iron
"Heads" before Roasting	100	23.12%	20.72%	0.90	7.65	12.12%
"Heads" after Roasting	96.3	6.26	....	....	....	....
"Tails" after Leaching	55.4	....	1.3	1.62*	13.756	10.9

* **(Calculated values)**

Total Iron going into solution...50.2 %

Extraction of Copper...95.50%

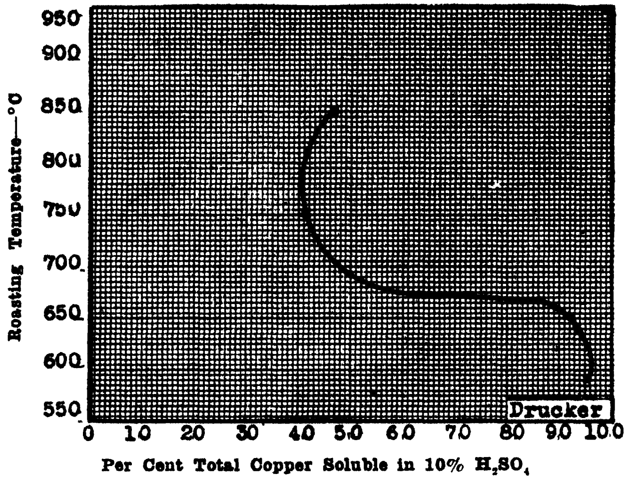


Figure 3. Broadly plotted curve, showing the relation of roasting temperatures to solubility of copper in 10% H^2SO^4 solution. Ore from Index Copper Co. (—100M)

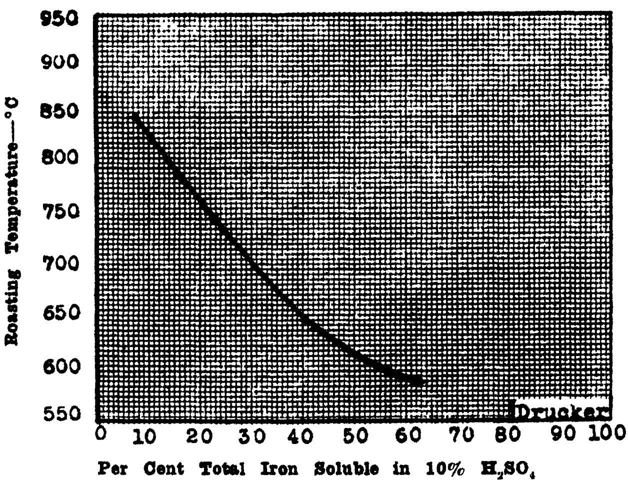


Figure 4 Broadly plotted curve, showing the relation of roasting temperatures to solubility of iron in 10% H^2SO^4 solution. Ore from Index Copper Co. (—100M)

The reduction in weight after roasting is probably due to the presence of gangue minerals. With an ordinary clean concentrate the weight after roasting will be greater than the original weight.

Electrolytic Deposition:

Attempts were made to electrolyze the solutions obtained from leaching the roasted calcine, but without very satisfactory results. The solution contained 34 grams of copper and 10.5 grams of iron per liter. A fairly firm deposit could be obtained when operating at a current density of 15 amperes per square foot, but the current efficiency was very low due to the presence of a large amount of ferric iron The voltage drop between the anode and cathode was two volts

CHEMISTRY

Roasting:

To attain the maximum extraction it is desirable to give the ore a (part) sulphatizing roast In sulphide copper ores the copper exists as cupric (CuS) and cuprous (Cu_2S) sulphide, and the iron as FeS and FeS_2. At comparatively low temperatures (roasting) the following reactions take place

1. $FeS_2 + O_2 + \text{heat} = FeS + SO_2$
2. $2\,FeS + 3\,O_2 = 2\,FeO + 2\,SO_2$
3. $2\,CuS + 3\,O_2 = 2\,CuO + 2\,SO_2$
4. $2\,Cu_2S + 3\,O_2 = 2\,Cu_2O + 2\,SO_2$
5. $Cu_2O + SO_2 + O_2 = 2\,CuO + SO_3$

The final result then for the low temperature roast is to convert the sulphides into oxides with the elimination of sulphur as SO_2. On increasing the temperature the iron is further oxidized as follows.

$3\,FeO + O = Fe_3O_4$

$2\,Fe_3O_4 + O = 3\,Fe_2O_3$

$FeO + SO_3 = FeSO_4$

$6\,FeSO_4 = Fe_2(SO_4)_3 + 2\,Fe_2O_3 + 3\,SO_2$

$Fe_2(SO_4)_3 = Fe_2O_3 + 3\,SO_3$

The ultimate result of roasting the iron is to convert it into ferric oxide. Under ideal conditions this reaction is complete at a low red heat or about 590° C.

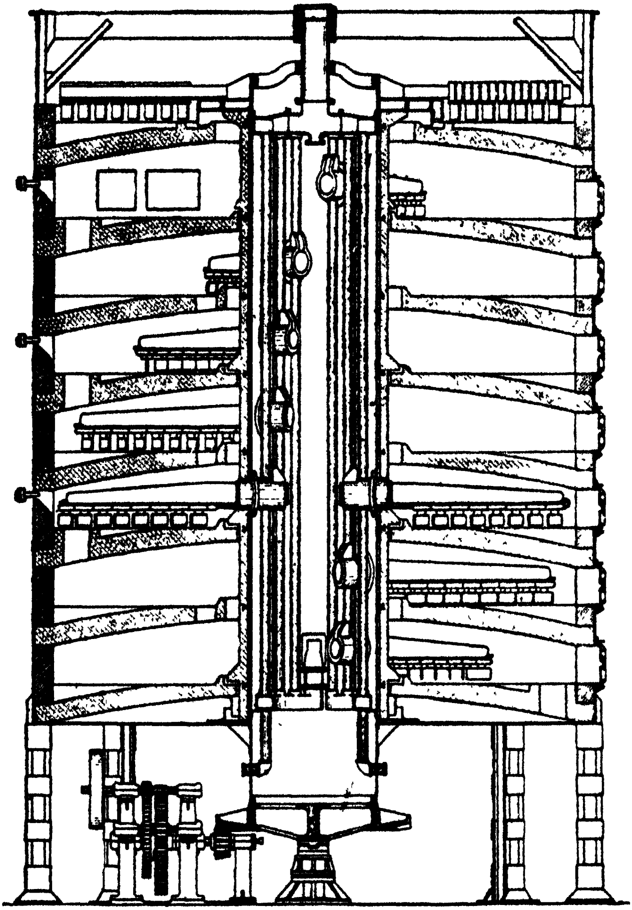


Figure 7—Wedge Type, Multiple-Hearth Roasting Furnace

At temperatures in excess of 590° C. the copper oxide previously formed reacts to produce copper sulphate as follows:

$CuO + FeSO_4 = CuSO_4 + FeO$

Or in other words the SO_3 given off by the decomposition of the iron sulphates reacts with the copper oxides to form copper sulphates.

If the temperature of roasting exceeds 650° C. the copper sulphate is decomposed into cupric oxide and sulphur trioxide, the reaction being complete at 700° C.

$CuSO_4 = CuO + SO_3$

Above 650° C the results show that the solubility of the copper compounds decreases very rapidly indicating that ferrites and silicates are formed. A further indication of this is that the color of the roasted products changed from red to black when the temperature exceeded 650° C.

The following reactions show the way in which chalcocite (Cu_2S), bornite (Cu_5FeS_4), chalcopyrite ($CuFeS_2$), and iron pyrite (FeS_2) break down when subjected to the roasting temperatures indicated.

Chalcocite: (430° to 650° C.)

1. $2\ Cu_2S + 3\ O_2 = 2\ Cu_2O + 2\ SO_2$
2. $Cu_2O + SO_2 + O_2 = 2\ CuO + SO_3$
3. $CuO + SO_3 = CuSO_4$
4. $2\ CuSO_4 = CuO, CuSO_4 + SO_3$
5. $CuO, CuSO_4 = 2\ CuO + SO_3$

Bornite: (500° to 700° C.)

1. $3\ Cu_5FeS_4 + 5\ O_2 = 4\ Cu_2S + 3\ FeSO_4 + CuSO_4 + SO_2$
2. $4\ Cu_2S + 4\ FeSO_4 + 11\ O_2 = 8\ CuSO_4 + 2Fe_2O_3$
3. $2\ CuSO_4 = CuO, CuSO_4 + SO_3$
4. $CuO, CuSO_4 = 2\ CuO + SO_3$

Chalcopyrite: (525° to 700° C.)

1. $3\ CuFeS_2 + 9\ O_2 = Cu_2S + 3\ FeSO_4 + CuSO_4 + SO_2$
2. $4\ Cu_2S + 4\ FeSO_4 + 11\ O_2 = 8\ CuSO_4 + 2\ Fe_2O_3$
3. $2\ CuSO_4 = CuO, CuSO_4 + SO_3$
4. $CuO, CuSO_4 = 2\ CuO + SO_3$

Pyrite: (325° to 750° C.) (Removed by selective flotation.)

1. $FeS_2 + O_2 = FeS + SO_2$
2. $2\ FeS + 3\ O_2 = 2\ FeO + 2\ SO_2$
3. $6\ FeO + O_2 = 2\ Fe_3O_4$
4. $FeO + SO_3 = FeSO_4$
5. $4\ Fe_3O_4 + O_2 = 6\ Fe_2O_3$
6. $2\ Fe_3O_4 + SO_3 = 3\ Fe_2O_3 + SO_2$
7. $6FeSO_4 = Fe_2(SO_4)_3 + 2\ Fe_2O_3 + 3\ SO_2$
8. $Fe_2(SO_4)_3 = Fe_2O_3 + 3\ SO_3$
9. $4\ FeS_2 + 11\ O_2 = 2\ Fe_2O_3 + 8\ SO_2$

Leaching:

Leaching consists simply of dissolving certain of the roasted products in dilute sulphuric acid. The copper and iron sulphates are water soluble and readily enter the solution.

$$CuO + H_2SO_4 = CuSO_4 + H_2O$$
$$FeO + H_2SO_4 = FeSO_4 + H_2O$$
$$Fe_2O_3 + 3\ H_2SO_4 = Fe_2(SO_4)_3 + 3\ H_2O$$

The latter reaction does not take place very rapidly in dilute sulphuric acid, and it is therefore desirable to oxidize as much as possible of the iron to Fe_2O_3 in the roast, in order to prevent it from entering the solution.

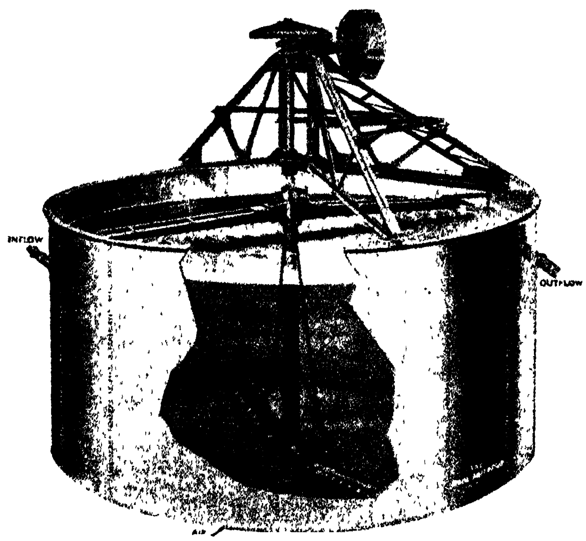


Fig. 8—The Dorr Agitator

Electrolysis:

The principle of the electrolytic deposition of copper may be illustrated by the following equation:

$$CuSO_4 + H_2O + \text{Electrolysis} = Cu(\text{cathode}) + O(\text{Anode}) + H_2SO_4$$

Therefore for every pound of copper deposited, 1.54 pounds of sulphuric acid will be regenerated.

The presence of iron in the solution lowers the current efficiency a great deal (Fig. 5 and 6). Any ferrous sulphate present will be oxidized at the anode to ferric sulphate which is a solvent for metallic copper, and will dissolve it from the cathode, thereby lowering the current efficiency.

$$2\ FeSO_4 + H_2SO_4 + O\ \text{(at anode)} = Fe_2(SO_4)_3 + H_2O$$

$$Fe_2(SO_4)_3 + Cu = 2\ FeSO_4 + CuSO_4$$

For successful electrolysis, therefore the amount of ferric iron in solution must be very low.

TESTS ON ORE FROM ROYAL DEVELOPMENT COMPANY

From the previous tests it was seen that some method of overcoming the deleterious effects of ferric iron on the electrolysis would have to be worked out Two known methods of doing this are feasible. The first is to keep the iron reduced to the ferrous state by means of sulphur dioxide (Greenawalt's method) obtained from the roasting furnaces The second is to chemically purify the solution prior to electrolysis. The first method offers many advantages, but must be applied throughout the electrolytic deposition, because the iron is being continuously re-oxidized at the anodes of the cells It is therefore not a cure but only a means of reducing the harmful effects of the iron in lowering the current efficiency

Ferric iron may be chemically precipitated from a copper sulphate solution by proper air (oxygen) agitation in the presence of sufficient copper oxide (Further investigations of the use of air are being made at the present time) Ferrous iron must first be oxidized to the ferric state This may be done either by air agitation, or by the addition of manganese dioxide to the solution The reactions involved are as follows

1. $3\ CuO + Fe_2(SO_4)_3 = 3\ CuSO_4 + Fe_2O_3$ (hydrated)
2. $4\ CuO + 4\ FeSO_4 + O_2 = 4\ CuSO_4 + 2\ Fe_2O_3$ (hydrated)
3. $2\ FeSO_4 + 2\ H_2SO_4 + MnO_2 = Fe_2(SO_4)_3 + MnSO_4 + 2\ H_2O$

The manganese sulphate is changed to manganese dioxide and precipitated during electrolysis. It may be recovered from the bottom of the cells and reused. The precipitation of the iron (Fe_2O_3) occurs much more rapidly in a neutral than in an acid solution It would therefore be desirable to add an excess of calcine to the leach in order to neutralize the solution and promote the iron precipitation. These reactions have been known to chemistry for a long time

To determine the applicability of this method of purifying the solution, tests on chalcopyrite ore from the Royal Development Company were run, the results of which follow.

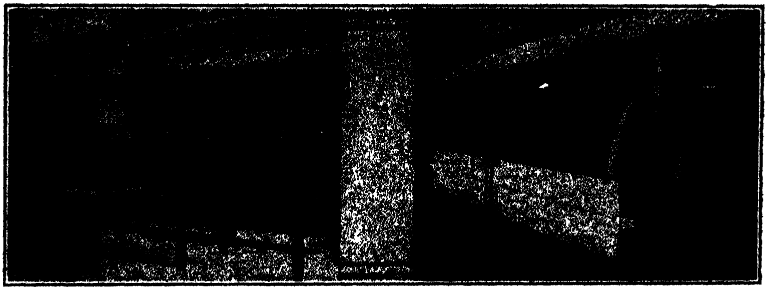


Figure 24. Oliver Continuous Filters

Nature of Ore Tested:

The ore, a large massive piece of chalcopyrite, came from the property of the Royal Development Company, Leavenworth, Washington. It consisted mostly of large crystals of chalcopyrite and considerable pyrrhotite. Calcite is also present in large crystals dispersed throughout the chalcopyrite. On one side of the massive piece of chalcopyrite was several pieces of chlorite, indicating possibly that this was the gangue rock

A microscopic examination revealed the fact that the amount of pyrrhotite ore was considerably greater than at first supposed. The particles could be readily distinguished by moving a magnet beneath the stage and thus producing a motion of the pyrrhotite particles. The latter crushed finer than the chalcopyrite, which tended to remain in coarse crystals, although fines were also present. The calcite crystals were also quite prominent, but only a few crystals of bornite could be seen.

Quantitative Analysis of the Ore.

Copper	21.73%
Iron	29.31%
Sulphur	28.12%
Calcium Carbonate	12.47%
Gold	0.05 oz/T.
Silver	5.2 oz./T.

DATA AND RESULTS—ROASTING TESTS

Test No.	1.	2
Weight Before Roasting	100g	400g.
Weight After Roasting	104.5 g.	417.3g.
Ground to Pass Mesh	100.	100.
Time of Roasting	6 hrs.	8 hrs.
Temperature	595° C.	625° C.
% Cu. Before Roasting	21.73%	21.73%
% Cu. After Roasting	20.8%	20.83%
% Fe. Before Roasting	29.31 %	29.31%
% Fe. After Roasting	28.15%	28.15%
Sulphur Before Roasting	28.12%	28.12%
Sulphur After Roasting	6.1%	5.8%

When first placed in the furnace the concentrate sintered considerably, but after once breaking up, it remained in a fine state of subdivision during the rest of the roast.

LEACHING TESTS

The calcine from Roast No. 1 and No. 2 was leached with 6.5% H_2SO_4 by agitation with the following results:

Sample from Roast Number	1	2
Analysis of "Heads" Copper	20.8%	20.83%
Iron	28.15%	28.15%
Total Cu. soluble in H_2O	48.1%	54.7 %
Total Fe. soluble in H_2O	0.95%	0.4 %
Strength of Leach Solution	6.5%	6.5 %
Solution used	225.0 cc.	900.0 cc.
Grams Calcine used	75.0 g.	300.0 g.
Weight of 'Tails"	38.0 g.	142.0 g.
Analysis of "Tails" Cu.	0.6%	0.9 %
Fe.	45.13%	49.4 %
Au.	0.08 oz./T.	0.08oz./T.
Ag.	10.05 oz./T.	10.05oz./T.
Extraction of Copper	98.5%	97.9 %
Extraction of Iron	18.8%	16.9 %

TEST TO DETERMINE SOLUBILITY OF IRON AND COPPER

Ore, roasted at 600° C., was leached for 4 hours at 65° C. with various strengths of H_2SO_4 to determine the solubility of the iron and copper. The following results were obtained:

Weight of Sample	25.0 grams
Solution	250.0cc.
Analysis of Calcine-Cu.	20.8%
-Fe.	28.15%

Test. No.	% H_2SO_4	% Total Soluble Fe	% Total Soluble Cu.	Grams Cu. Per Liter	Grams Fe. Per Liter
1	0.00	0.60	52 6	60.0	0.9
2	1.85	4.10	94.6	60.0	3.5
3	4 06	9.22	97.4	60.0	7.7
4	7.81	18.47	98.1	60.0	15.3
5	10.19	35.41	98.3	60.0	29.2
6	12.18	41.80	98.3	60.0	34.3
7	13.58	43.60	98.4	60.0	35.8

Remarks·

Columns 5 and 6 in the above table were computed from the total solubilities of the iron and copper, assuming that the resulting solution contained 60 grams of copper per liter. It is used simply as a basis of comparison

WATER, LOW ACID AND HIGH ACID LEACH

100 grams of calcine, roasted at 600° C. was leached first with water, then with 1.64% H_2SO_4, and finally with 5.8% H_2SO_4. Acid was added to the low acid leach at intervals in such amounts that the strength never exceeded 1.64%, and was over 1% when leaching was completed.

	H_2O Leach	Low Acid Leach	High Acid Leach
Weight of Sample	100.0 g.	72.0 g.	58.0 g.
Analysis—Cu.	20.8 %	13.64 %	1.07 %
Fe	28.15 %	38.60 %	47.15 %
Solution	200.0 cc.	200.0 cc.	200.0 cc.
Strength of solution	0.0 %	1.64 %	5.8 %
Temp. of Leach	70° C.	70° C.	70° C.
Time of Leaching	4 hrs.	6 hrs.	4 hrs.
Weight of Residue	72.0 g.	58.0 g.	48.0 g.
Solution Gms. Cu/Liter	55.0 g.	46.0 g.	2.7 g.
Solution Gms. Fe./Liter	1.5 g.	2.2 g.	12.0 g.
Residue Analysis—Cu.	13.64 %	1.07 %	0.2 %
Fe.	38.60 %	47.15 %	51 35 %
Extraction of Copper	52.88 %	93.9 %	84.5 %
Extraction of Iron	1.23 %	1.58 %	9.83 %

Note: Extraction percentages were figured consecutively in the above table. Total extractions were as follows:

Total Extraction of Copper	99.3%
Total Extraction of Iron	12.4%

NEUTRAL LEACH

300 grams of roasted calcine (600° C. Roast) was added to one liter of 1.4% H_2SO_4 solution. This was heated and leached for 8 hours. The following amounts of acid were added:

At end of 1 hour	10.8 g.
At end of 2 hours	11.3 g.
At end of 3 hours	10.6 g.
At end of 4 hours	11.5 g.

The final acid strength was 0.95%. The leach solution contained 2.7 g. of iron and 55.2 g. of copper per liter.

After filtering, 3 grams of MnO_2 was added to the solution. This was heated and allowed to stand one hour. An excess of calcine was then added and the solution allowed to stand, with frequent stirring, until all free acid was consumed. It was then re-filtered. The resulting solution contained 1.5 g. of iron and 59.3 g. of copper per liter.

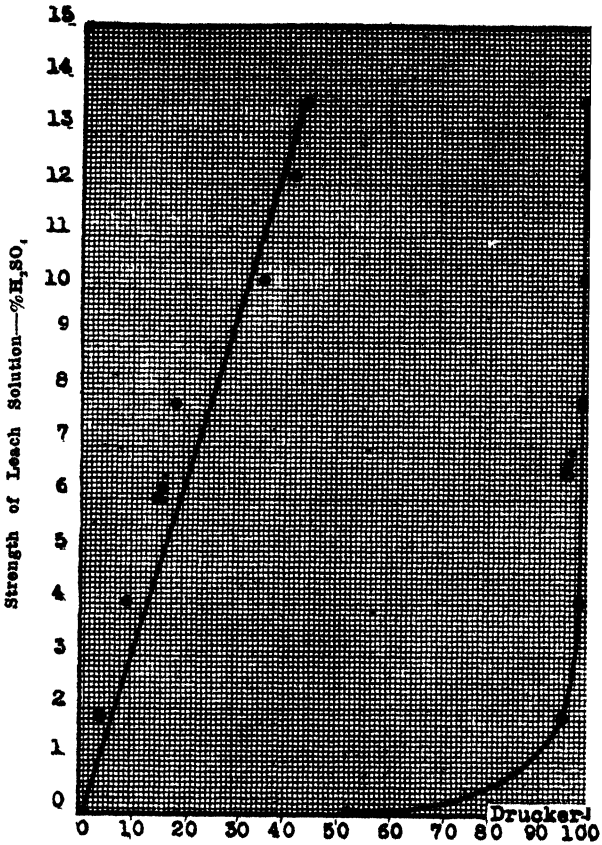


Figure 9. Solubility of Iron and Copper (Roasted Calcine) in various strengths of Sulphuric Acid. Ore from Royal Development Co.

The solution was then placed in an agitator, 5 grams of CuO added, and oxygen from a pressure tank bubbled through. At the end of 20 minutes all but 0.005% of the iron was precipitated.

PURIFICATION TEST

An acid solution containing 41 grams of copper and 5.1 grams of iron ($FeSO_4$) per liter was purified by addition of MnO_2 and oxygen agitation in the presence of an excess of CuO. 5 grams of MnO_2 was first added to the solution to oxidize the iron as much as possible. Three

grams of CuO were then added to the solution, and it was heated and agitated for 30 minutes. An assay showed that the solution now contained 2.75 grams of iron per liter. An excess of CuO was then added, and the solution agitated by means of oxygen with the following results:

After 0 Minutes, Oxygen Agitation, Fe. Content = 2.75 g./Liter
After 5 Minutes, Oxygen Agitation, Fe. Content = 1.80 g./Liter
After 10 Minutes, Oxygen Agitation, Fe. Content = 1.40 g./Liter
After 15 Minutes, Oxygen Agitation, Fe. Content = 1.00 g./Liter
After 20 Minutes, Oxygen Agitation, Fe. Content = 0.50 g./Liter
After 25 Minutes, Oxygen Agitation, Fe. Content = 0.10 g./Liter
After 30 Minutes, Oxygen Agitation, Fe. Content = Trace

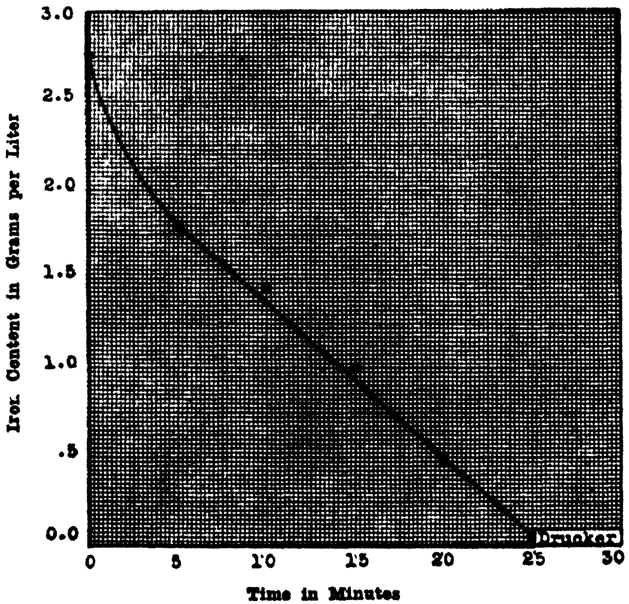


Figure 12. Precipitation of Iron from a Copper Sulphate Solution by oxygen agitation in the presence of Copper Oxide.

Treatment of Tailing:

The treatment of the tailing in those cases where the concentrate contains worth while values in gold and silver has not been completely worked out.

Cyanidation seems to be the most logical method of treatment. Several writers have agreed that after removing the copper and thoroughly washing the tailing, there is no reason why cyanidation could not be applied to extract the gold and silver. Middleton① found that the tailing from an acid leach could be cyanided with a recovery of 90% of the gold and a consumption of 1.5 lb. of cyanide per ton. His copper extractions in the laboratory were 96.5, 97.9, and 98.7%. From a 100-ton test he extracted 95% of the copper. He states that 85 to 95% of the copper can be converted to $CuSO_4$ in roasting.

Two cyanide tests conducted on tailing from our own tests gave an extraction of 97.34% and 93% of the gold respectively. The cyanide consumption, however, was quite high, but it is believed that it can be reduced by proper water and alkaline washes. Further research is now under way the results of which will appear in Progress Report No II.

DISCUSSION OF RESULTS

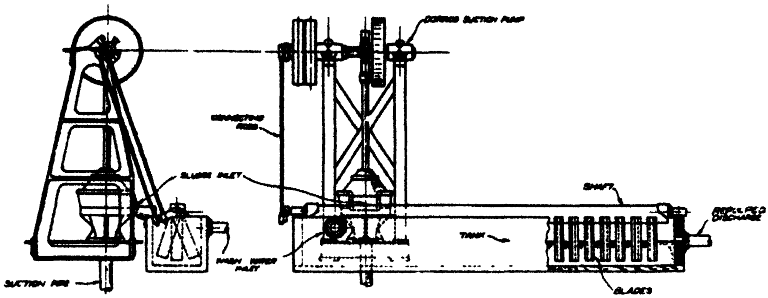
Roasting:

The best results were obtained when the roast was carried on at approximately 600° C. At this temperature about 50% of the copper is converted into a water-soluble copper sulphate which is found to cause an excessive regeneration of acid in the cells. However, if the roasting was carried on at such a temperature that more of the copper sulphates were decomposed, insoluble compounds of copper were formed. Therefore, the only thing to do is to roast at the temperature that will give a maximum solubility of the copper (about 50% instead of 80 to 90% water-soluble copper) and control the acid content of the electrolyte by other means. By-passing a portion of the electrolyte at the end of each leaching cycle, or filtration through beds of limestone or calcium carbonate, are two possible ways in which the strength of acid can be controlled. We are not sure of the limestone method; this will have to be tested and the results reported in Progress Report No. II.

A multiple-hearth muffle roasting furnace (Wedge Type Fig. 7) has been successfully employed at low temperatures for roasting② copper sulphides. On concentrate high in sulphur, that is, 20% to 35%, the

① "Recovery of Copper from Flotation by Leaching," by P. C. Middleton, M. & S. P., June 7, 1919.
② Utley Wedge gives the results of roasting in the A.I.M.E. Vol. XLIV (1912).

material may be reduced to as low as 6% to 9% sulphur without the use of fuel. With a well designed modern roasting plant, treating 100 to 200 tons of sulphide per 24 hours, there should be no reason why the cost of roasting cannot be kept down to between $0.50 and $1.00 per ton.



THE DORRCO REPULPER

Figure 19

Leaching

In the great majority of copper leaching plants now in operation, the leach solution is never reduced to neutrality. The acidity is merely reduced by coming in contact with the ore, but when it leaves the system, it is still quite strongly acid. Results of the neutral leach and purification tests show that in the treatments of the roasted concentrate, it is desirable to have a neutral solution in order to promote the precipitation of the iron It will be necessary, therefore, to divide the leaching operation into two parts—a neutral leach, to which an excess of calcine is added, and a low acid leach to which an excess of acid is added. The strength of acid should be kept low in order that only a small amount of iron will dissolve (See Fig. 9) It may be desirable to regulate this strength at such a point that all the iron dissolved in the low acid leach will be precipitated by the excess of calcine in the neutral leach.

In the low acid agitators the maximum strength of acid does not necessarily have to control the amount of copper that is dissolved per ton of solution. Water, solids, and cell acid can be added in such proportions that the maximum acidity does not exceed a certain point (say 2% H_2SO_4). As the acid is neutralized more can be added until a solution containing at least 60 grams of copper per liter is built up

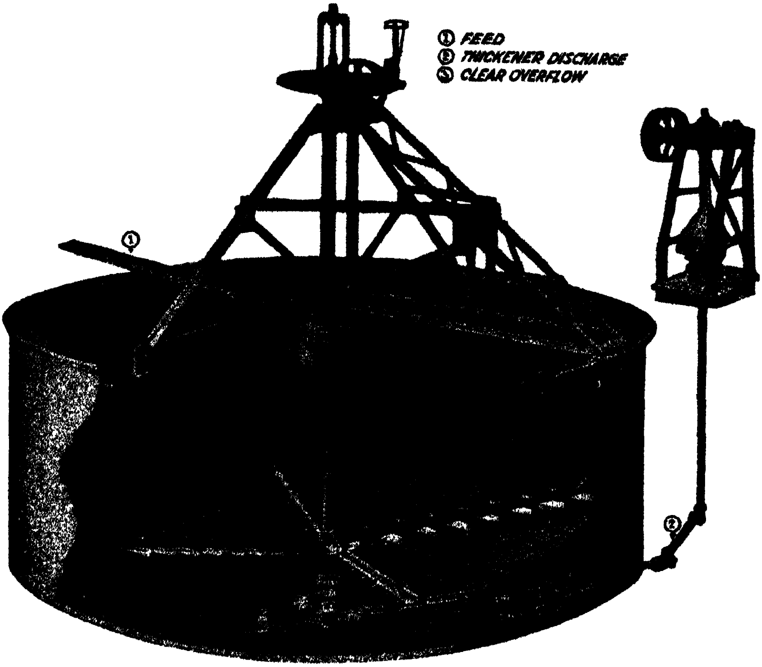


Figure 11. The Dorr Thickener

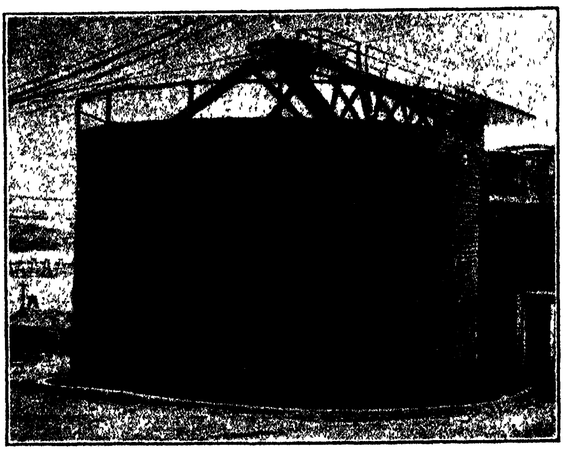
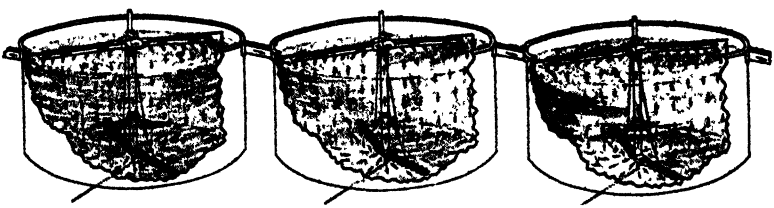


Figure 17. Dorr Agitator 37 Feet by 22 Feet at the Golden Cycle M. & R. Co.

If all of the iron dissolved in the low acid leach is not precipitated by the excess of copper oxide in the neutral agitators, it may be necessary to subject it to additional purification treatment. Increasing the number of Drucker agitators and the time of treatment in the neutral leach, however, should accomplish the same result, because the copper oxide contained in the excess of calcine will precipitate the iron if it is in contact with it long enough. While oxygen agitation was used in the tests performed, proper air agitation should serve as well, although the reaction may not take place so rapidly.

The results show that only from 90% to 95% of the copper is soluble in 2% H_2SO_4 (Fig. 9), and if the strength is increased much beyond this, an excessive amount of iron enters the solution Figuring on this basis, it may be necessary to have a high acid leach for the purpose of removing the small percentage of copper, which is insoluble in the lixiviant used in the low acid leach. At the same time a great deal of iron will be dissolved, which makes it impractical for the resulting liquor to be returned to the neutral leach. However, since it may be necessary to by-pass a certain percentage of the cell acid at the end of each leaching cycle in order to prevent the accumulation of an excessive amount of acid, there is no reason why a portion of this by-pass should not be agitated with the residues from the low acid leach, prior to denuding it of copper and discarding it. In this way a high percentage of the copper (over 98%) should be removed from the residues.



CONTINUOUS AGITATION WITH THREE DORR AGITATORS. ARROWS SHOW DIRECTION OF PULP MOVEMENT.

Figure 10.

Acid-proof Dorr Agitators and Thickeners (See Fig. 8 and 11), which are efficient and common equipment in other cyanidation hydrometallurgical processes are well adapted to the extraction of copper from high grade concentrates. In the neutral leach, the great importance of finely

divided air bubbles to insure the oxidation of ferrous iron, makes an agitator of the Drucker type (Fig. 13) worthy of consideration; the decantation principle also tends to work all the dissolved copper to the head of the system as soon as possible; it has already been tried out in cyanide plants.

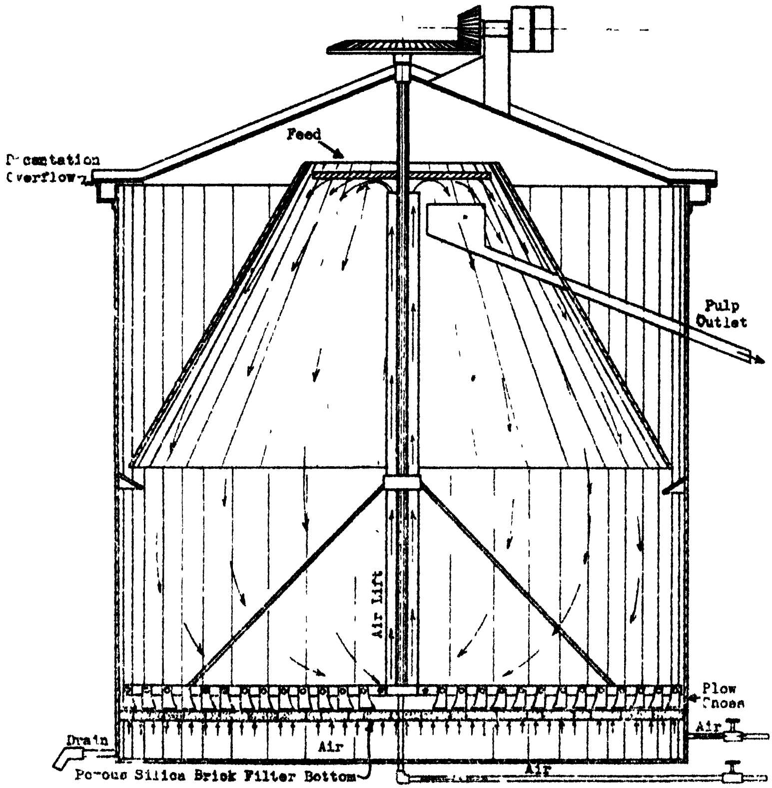


Fig. 13—DIAGRAMMATIC SECTION OF DRUCKER AGITATOR

Figures 14, 15, and 16 show various methods of connecting up leaching systems for the treatment of copper calcine. Figure 14 is the ordinary method used for leaching some oxidized ores, where the iron accumulation is not much of a problem. Figures 15 and 16 show systems worked out for treating roasted sulphide concentrates in accordance with the results

obtained in our tests. Figure 15 has a neutral and low acid leach only, and assumes that a high acid leach is unnecessary in order to extract nearly all the copper. Figure 16 shows a system with neutral, low acid, and high acid leach.

In any hydrometallurgical operation the amount of dissolved values lost in the discard of solutions is quite important. In the case of copper sulphides where cyanidation of the tailing is contemplated, it is doubly important that they be thoroughly washed, and as much of the soluble copper as possible removed before being cyanided. It is also quite necessary to know in what part of the leaching system the dissolved copper values lie, and what amount of work is being done by each of the machines. For these reasons, illustrations of the methods of calculating dissolved values in all parts of the systems shown in Figures 14, 15, and 16, are given, along with the conditions assumed in each case.

The Dorrco Filter—Drive End **Cake Discharge End**

Figure 20

The Dorrco Filter is a continuous rotary vacuum filter, with the filtering medium on the inside of the drum. One end of the drum is closed, while the other is open for cake discharge and to permit observation of the filter operation.

The feed is usually introduced through a pipe in the closed end and flows into the bath of pulp which covers the filter cloth. The force of gravity and the application of vacuum form a cake against the cloth and as the drum revolves the cake is dewatered, and washed if desired, until it reaches the discharge point near the top of the drum. Pulsations are applied to the cloth at the discharge point causing the cake to fall freely into the discharge hopper. If desirable, the cloth can be washed before it again enters the pulp bath.

The Dorrco Filter presents several distinctive features. Some of the more notable advantages are:—Gravity assists both cake formation and cake discharge; floor space requirements are small as no external tank is needed; coarse segregating materials can be handled without trouble; the whole cloth or any portion of it can be changed readily.

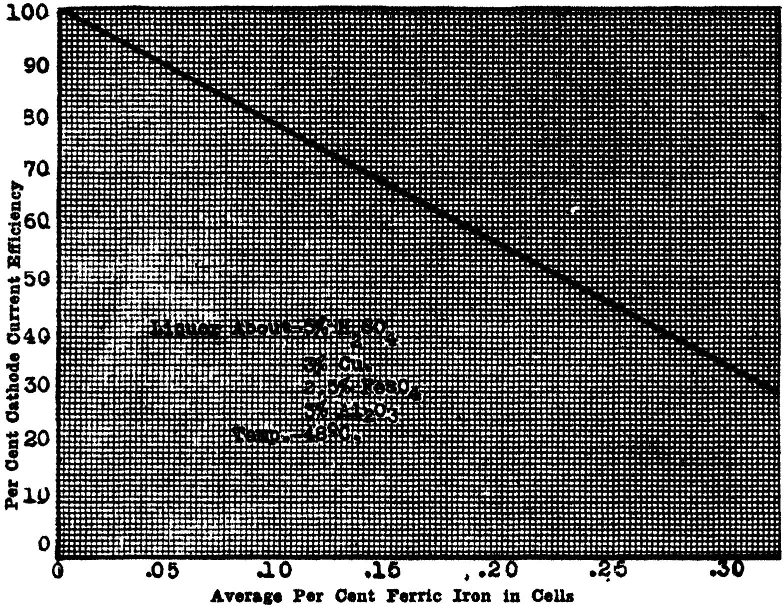


Figure 5. Effect of Ferric Iron on Current Efficiency
(According to Addicks)

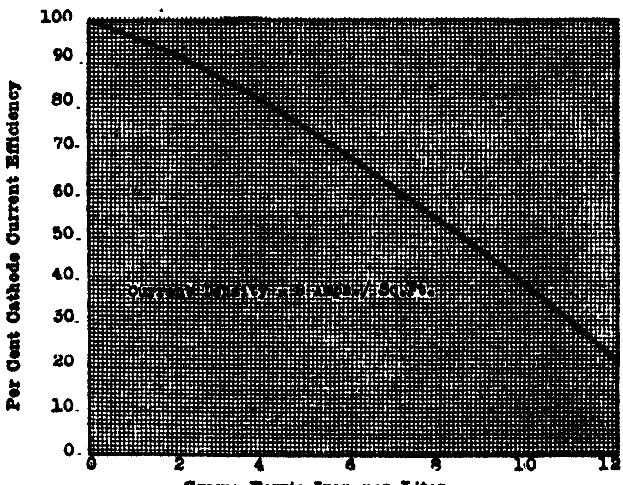


Figure 6. Effect of Ferric Iron on Current Efficiency.
(According to Middleton)

There are other possible variations in the method of leaching the copper from the roasted calcine. For instance, a preliminary water leach, prior to the acid leach, would remove nearly all the water-soluble copper (about 50% of the total copper) and produce a practically pure solution, because little of the iron remains in the water-soluble form after roasting to the required temperature. This would reduce the number of tons of solution which must be purified to one half, but would complicate the system somewhat.

Electrolysis:

Electrolytic tests were not carried out in any great detail. Purified electrolyte, however, containing 62 g. of copper and 0.5 g. of iron per liter was electrolyzed in a cell using copper sheet cathodes and lead anodes. A cathode efficiency of 90.8% was attained with a current density of 12 amperes per square foot of cathode depositing surface. As long as the circulation of the electrolyte was maintained the deposit was smooth and firm. The voltage-drop between anode and cathode was 2.0 volts. We are continuing our investigations with different kinds of anodes hoping to improve the current efficiency. The results will be published in our Progress Report No. II.

ORDINARY COUNTER-CURRENT DECANTATION SYSTEM NO. I USED FOR EXTRACTING COPPER FROM OXIDIZED (-100 M) COPPER ORE SLIMES.

CALCULATIONS FOR DISSOLVED VALUES

Conditions Assumed:

1. 100 tons of calcine, 20% copper, treated per 24 hours with an extraction of 98% of the copper.

2. Discharge from thickeners with 50% moisture. (1:1).

3. 80% of the copper enters the solution in the agitators, 2% in each of the thickeners V, W, X, and Y, and 12% in Thickener U.

4. Weight of solids reduced to 50 tons after agitation.

5. 75 grams of copper enters the solution per liter during each leaching cycle.

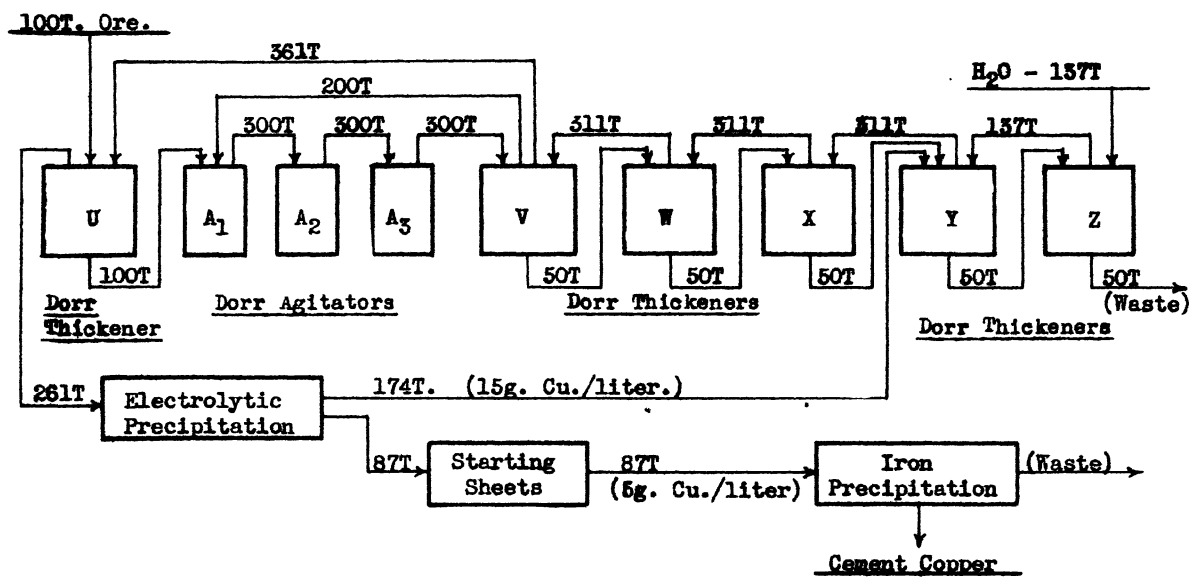


Figure 14. Ordinary Counter-Current Decantation System used for Extracting Copper from Oxidized Copper Ore Slimes. All figures (50T) refer to solution tonnages.

A. E. Drucker

6. ⅓ of the solution by-passed at the end of each leaching cycle and ⅔ returned to the circuit. The ⅔ contains 15 grams of copper per liter after electrolysis. The ⅓ is electrolyzed down to 5 grams per liter in the starting sheet division of the plant, prior to the scrap iron precipitation.

Calculations:

Equating out of and into each thickener:

1. $261U + 100U = 361V + 4752$ lbs. Cu.
2. $561V + 50V = 100U + 200V + 311W + 31{,}680$ lbs $+ 792$ lbs
3. $311W + 50W = 50V + 311X + 792$ lbs.
4. $311X + 50X = 311Y + 50W + 792$ lbs.
5. $311Y + 50Y = 137Z + 50X + (174 \times 30$ lbs.$) + 792$ lbs
6. $50Z + 137Z = 50Y + 137H_2O$.

Solving:

$U = 170.9$ lbs. Copper per ton of solution.
$V = 157.76$ lbs.
$W = 48.76$ lbs.
$X = 28.76$ lbs.
$Y = 23$ lbs.
$Z = 6.1$ lbs. Copper per ton of solution to waste.

CALCULATIONS FOR CONTINUOUS COUNTER-CURRENT DECANTATION WASHING AND LEACHING SYSTEM NO. 2.

Conditions Assumed:

1. 100 tons of roasted calcine, 20% Cu., treated per 24 hours, with an extraction of 98% cu. in the neutral and low acid leach.

2. 75 grams of copper enters the solution per liter in the neutral and low acid leach during each leaching cycle.

3. 25% of the total copper dissolved is in solution when the solids leave agitator T, 40% when they leave agitator U, and 50% when they leave agitator V.

4. The remaining 50% is dissolved equally in agitators A_1 A_2 A_3.

5. Weight of solids reduced to 75 tons in neutral agitators, and to 60 tons in low acid agitators.

6. ⅓ of the solution is by-passed at the end of each leaching cycle, and ⅔ returned to the low acid leach. This ⅔ contains 15 grams of copper per liter.

Calculations:

1. 98% × 20% × 100T. or 19.6 tons of copper enters the solution per 24 hours.
2. Therefore: $\frac{19.6 \times 100}{7.5}$ or 261 tons of solution must overflow Thickener S per 24 hours, if this solution dissolves 75 grams of copper per liter.

Note: All solution tonnages are the weight of water of specific gravity 1, and do not take into consideration the weight of the dissolved materials in the solution.

Let S, T, U, V, W, X, Y, Z, F_1, F_2, F_3, and R, equal the value in pounds of copper per ton of solution in the respective thickeners, agitators and filters.

Equating out of and into each thickener, filter, and agitator, we have:

1. $100S + 261S = 361T$.
2. $361T + 200T = 100S + 461U + 9{,}800$ lbs. Cu.
3. $461U + 200U = 200T + 461V + 5{,}880$ lbs.
4. $461V + 200V = 200U + 461W + 3{,}920$ lbs.
5. $75W + 461W = 200V + 263X + 36(3/2F_1)^* + 37W$
6. $37W + 36(3/2F_1)^* + 12F = 75W + 10\ H_2O$
7. $401X + 60X = 311Y + 138X + 12F_1 + 19{,}600$ lbs
8. $311Y + 60Y = 311Z + 60X$
9. $311Z + 60Z = 60Y + 77R + 30Z + 30(3/2F_2)^* + 174 \times 30$
10. $30Z + 30(3/2F_2) + 10F_2 = 60Z + 10\ H_2O$
11. $77R + 60R = 10F_3 + 30R + 30(3/2F_3)^* + 67\ H_2O$
12. $30R + 30(3/2F_3) + 10F_3 = 60Z + 10\ H_2O$

* Displacement efficiency of filter.

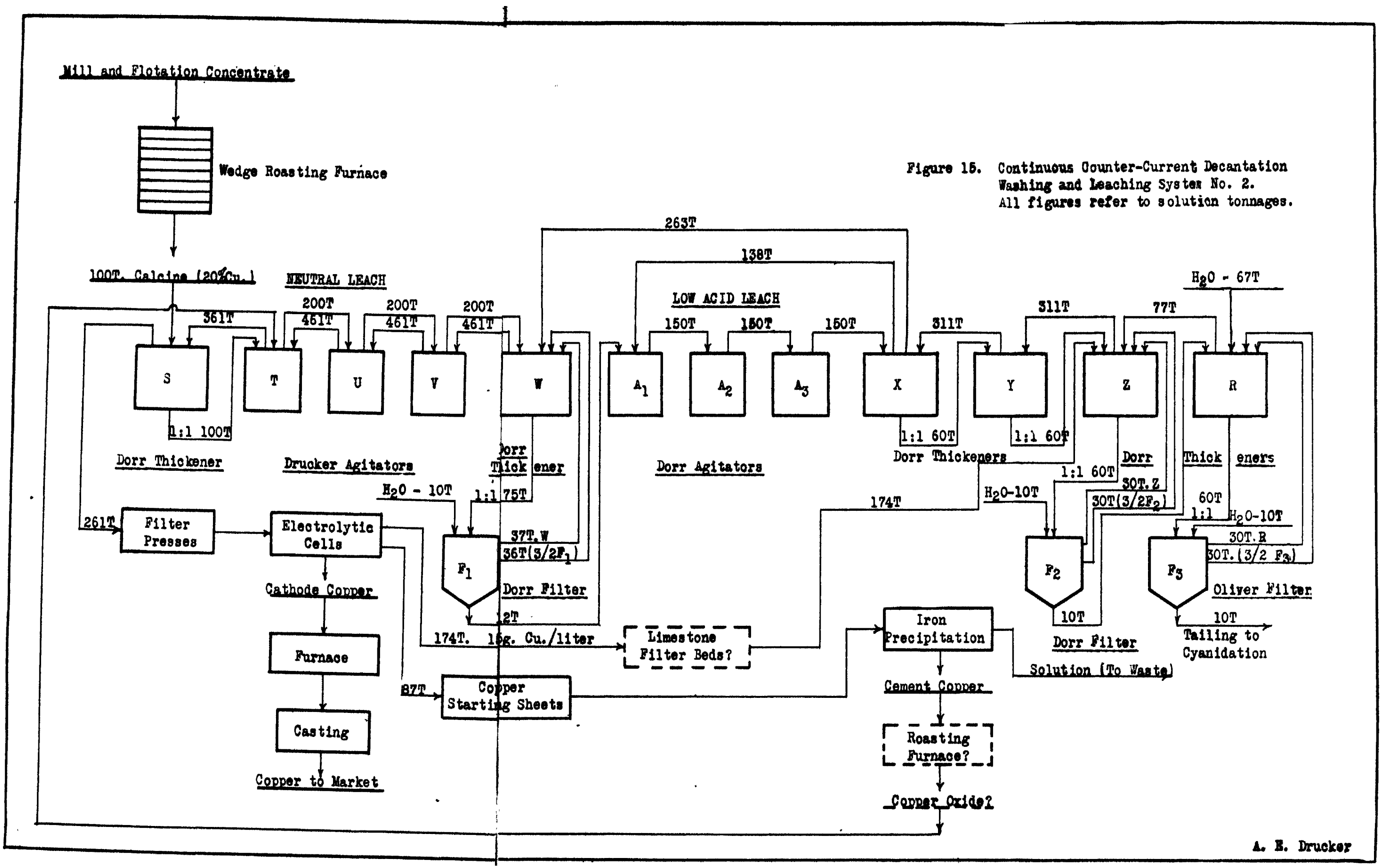


Figure 15. Continuous Counter-Current Decantation Washing and Leaching System No. 2. All figures refer to solution tonnages.

Solving:

1. $S = 170.3$ lbs. Cu./T. of solut.	7. $X = 97.2$ lbs.
2. $T = 170.3$ lbs.	8. $Y = 35.5$ lbs.
3. $U = 149.0$ lbs.	9. $Z = 23.6$ lbs.
4. $V = 127.1$ lbs.	10. $F_2 = 12.9$ lbs.
5. $W = 109.1$ lbs.	11. $R = 1.56$ lbs.
6. $F_1 = 62.8$ lbs.	12. $F_3 = 0.85$ lbs. per ton of solut. waste.

Therefore: Solution loss $= 0.85 \times 10T. = 8.5$ lbs. Cu. per 20T. Copper.

Solution Cu. Recovery = 99.5%

Amount of cement copper formed = 870 lbs. per 20T. Cu.
= 2.18%

CALCULATIONS FOR CONTINUOUS LEACHING AND WASHING SYSTEM NO. 3.

Assuming that a High Acid Leach is necessary at the end of the System in order to obtain a high extraction of the copper

Conditions Assumed:

1. 100 Tons of roasted calcine, 20% Cu., treated per 24 hours, with an extraction of 94% of the copper in the neutral and low acid leach, and an extraction of 4% of the copper in the high acid leach.

2. 75 grams of copper enters the solution per liter in the neutral and low acid leach, during each leach cycle.

3. 25% of the copper dissolved in the neutral and low acid leach is in solution when the solids leave agitator T, 40% when they leave agitator U, and 50% when they leave agitator V. The remaining 50% is dissolved equally in agitators A_1, A_2, A_3.

4. Weight of solids reduced to 75 tons in the neutral leach, to 60 tons in the low acid leach and to 50 tons in the high acid leach

5. ⅓ of the solution by-passed at the end of each leaching cycle and ⅔ returned to the low acid leach. This ⅔ contains 15 grams of copper per liter. The ⅓ is reduced to 5 grams of copper per liter in the starting-sheet division of the plant, and then agitated with the tails from the low acid leach prior to denuding it of copper by precipitation on scrap iron and discarding.

CALCULATIONS FOR DISSOLVED VALUES

Let S, T, U, V, W, X, Y, Z, R, F_1, F_2, and F_3 equal the value in pounds of copper per ton of solution in the respective thickeners, agitators, and filters.

Equating out of and into each thickener, agitator, and filter, we have:

1. $251S + 100S = 351T$.
2. $351T + 200T = 100S + 451U + 9{,}400$ lbs.
3. $451U + 200U = 200T + 451V + 5{,}640$ lbs.
4. $451V + 200V = 200U + 451W + 3760$ lbs.
5. $451W + 75W = 200V + 296X + 30(3/2F_1)$
6. $326X = 75W + (167 \times 30 \text{ lbs.}) + (84 \times 0) + 18{,}800$ lbs.
7. $30X + 30(3/2F_1) + 10F_1 = 60X + 10\ H_2O$
8. $154Y = 10F_1 + 60Z + 84 \times 10 + 1500$ lbs.
9. $25Y + 25(3/2F_2) + 10F_2 = 50Y + 10\ H_2O$
10. $60Z + 50Z = 10F_2 + 50R + 25R + 25(3/2F_3)$
11. $100R = 50Z + 50\ H_2O$
12. $10F_3 + 25(3/2F_3) + 25R = 50R + 10H_2O$

Solving:

1. $S = 169.7$ lbs cu./T. of Solution.
2. $T = 169.7$ lbs.
3. $U = 148.9$ llbs.
4. $V = 127.2$ lbs.
5. $W = 109.2$ lbs.
6. $X = 98.1$ lbs.
7. $F_1 = 53.5$ lbs
8. $Y = 19.35$ lbs.
9. $F_2 = 10.2$ lbs.
10. $Z = 1.62$ lbs.
11. $R = 0.81$ lbs.
12. $F_3 = 0.43$ lbs. cu./T. of solution to waste.

Therefore: Solution loss $= 0.43 \times 10T. = 4.3$ lbs. Cu per 20 tons copper.

Solution Cu. Recovery = 99.75%

Amount of cement copper formed = 2870 lbs. per 20T. Cu.

= 7.18%

ELECTROLYSIS

The results on electrolysis are thus far quite meager, but they show that a good and practically pure deposit of copper can readily be made, and a high current efficiency obtained. Since the iron content of the electrolyte is so low, it may be possible to use carbon anodes, thus increasing the energy efficiency.

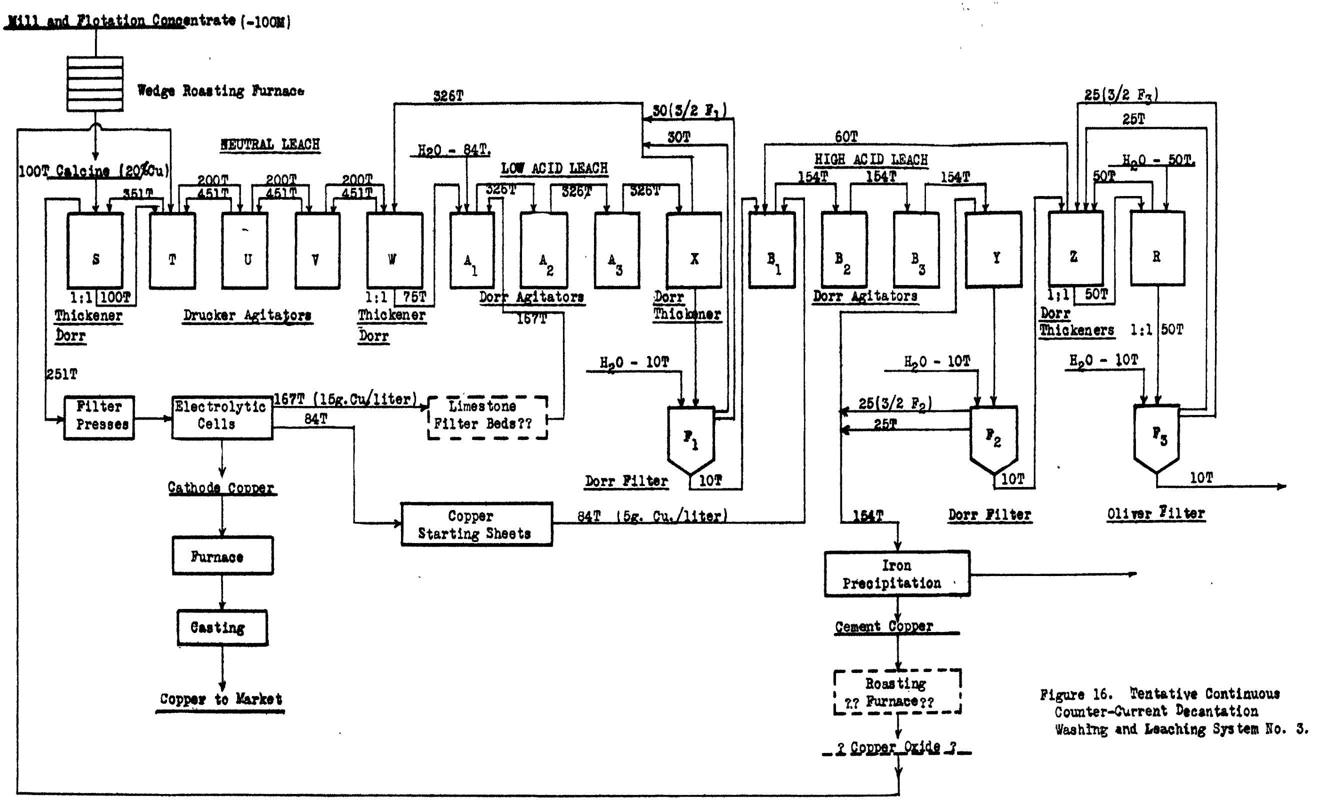


Figure 16. Tentative Continuous Counter-Current Decantation Washing and Leaching System No. 3.

The copper content of the electrolyte can vary from 60 to 100 grams per liter when entering the cells, and down to about 15 to 20 grams per liter when leaving them. The portion of the electrolyte which is by-passed to keep down the acidity could possibly be run through a special bank of cells, and the copper content economically reduced to 5 grams per liter, before running it through the scrap-iron launders or Hydrogen Sulphide Precipitation tanks to denude it of the last traces of copper. This part of the electrolysis can possibly be made the starting-sheet division of the plant.

We will continue the work of copper electrodeposition with such solutions resulting from the leaching of high-grade copper sulphide concentrate, and the results will be published in our Progress Report No. II

Figure 23. Tank house of Inspiration Consolidated Copper Co., at Inspiration, Arizona. Here the copper leached from the ore is precipitated electrolytically, using lead anodes.

CONCLUSIONS

The results of these laboratory tests so far as carried out indicate:

First: That by roasting at approximately 600° C it is possible to convert 94% of the copper into a form that is soluble in less than 2% H_2SO_4. At the same time all but approximately 4% of the total iron is rendered insoluble.

Second: That the remaining copper can be removed by leaching with a higher strength of acid so that a total extraction of 96 to 98% of the copper can be attained.

Third: That the iron entering the leach solution can be largely precipitated, after neutralization by CuO in the calcine, and oxidation with manganese dioxide, or oxygen from the air, or both

Fourth: That a solution of copper sulphate of high purity can be attained, from which the copper can be readily precipitated by electrolysis with a cathode efficiency of over 90%.

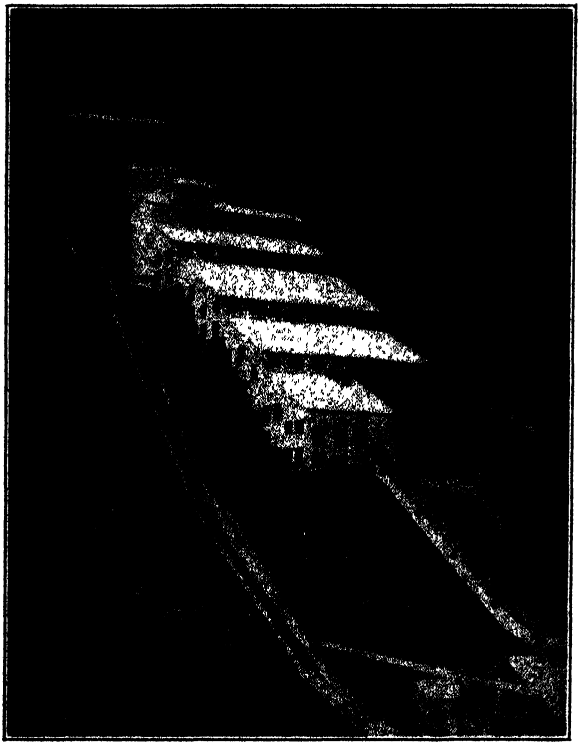


Figure 18. Copper Mill

A plant as suggested in the paragraph at the top of page 39, has been provided for and will be installed as soon as possible; it will include: Low-temperature Roasting, Purification by Neutral Leaching, Low-acid Leaching, Counter-current Decantation and Filtration, and Copper Electrodeposition.

Therefore, from the results so far obtained the following method of treatment for flotation sulphide copper concentrate is suggested for our next step of proceedure with our laboratory continuous treatment plant:*

1. Roasting the clean concentrate (-100M) at 600° C. (50% water-soluble copper) in a multiple hearth roaster until all the sulphides are practically decomposed.

2. Leaching the copper with dilute sulphuric acid (1.5 to 2%) and producing a neutral solution of copper sulphate by using a double leaching system.

3. If necessary, further purification of this solution by proper air agitation in the presence of copper oxide.

4. Electrolysis of the solution and precipitation of the copper on copper starting-sheet cathodes, with the subsequent regeneration of the sulphuric acid solvent. We aim to keep down the water-soluble ($CuSO_4$) copper to 50%, instead of 70 to 80% as some metallurgists have recommended, thereby preventing excessive amounts of regenerated H_2SO_4 acid which would be undesirable with our method of procedure.

5. Use a portion of the regenerated acid to dissolve more copper, and by-passing the remainder in order to keep the acid content of the electrolyte down If the amount by-passed for this purpose is excessive, the acidity may be reduced possibly by filtering through beds of limestone or calcium carbonate; however this will have to be proved by trial.

6. If necessary, agitating the tails from the above leach with the by-passed solution in order to remove a higher percentage of the copper.

7. Precipitation of the copper remaining in the by-pass after electrolysis on scrap iron, or by hydrogen sulphide, ** if the acidity is too high.

8. Converting the cement copper or copper sulphide precipitate thus formed into copper (CuO) oxide and returning it to the neutral-leach for purification.

9. Thoroughly washing the tailing, followed by cyanidation for the extraction of the gold and silver, if present in paying quantities.

It should be expressly understood that the process as here outlined is by no means a definite one. It is only the one which appears at this

* This has been suggested by certain metallurgists.

** The electrolyte can then be run continuously for a long period so as to allow for any troubles due to impurities in the solution.

time to be the most logical and feasible from the favorable small scale tests so far conducted in this laboratory. A small continuous plant may bring to light several changes which would alter the outline (flow-sheet) of this treatment considerably. The erection of such a plant as suggestted by Greenawalt at our laboratory is the next step toward determining the adaptability and merits of the process.** The results will be published in Progress Report No. II. The comparative costs and the economics of the

Fig. 21—American Continuous Filter (Disc Type)

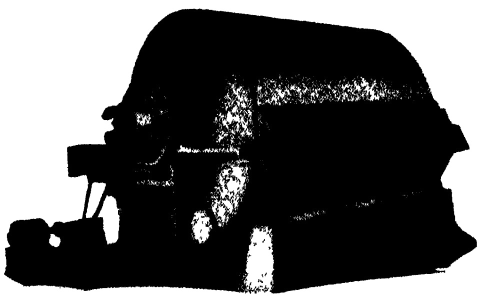


Fig. 22—Oliver Continuous Filter (Drum Type)

process must be carefully investigated. There is no better prospective field in metallurgy than with the hydro-metallurgical treatment and extraction of electrolytic copper from mill (flotation) copper sulphide con-

The electrolyte can then be run continuously for a long period so as to allow for any troubles due to impurities in the solution.

centrate. Let us hope that this work will encourage others to investigate the possibilities of this new field of metallurgy where the cost of producing electrolytic copper of high purity from flotation copper concentrate in our State with hydro-electric power at $\frac{1}{3}$ to 1 cent per kilowatt hour should not be more than 1.5 to 3 cents per pound depending upon the scale of operations.

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